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Technical Report: NAVTRAEQUIPCEN IH-321

THE EFFECTS OF VARIOUS FIDELITY FACTORS ON SIMULATED HELICOPTER HOVER

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The effects of the cues of aircraft motion, of delays in a visual scene, and of movement of a ship model were examined by measuring pilots' ability to hover a simulated helicopter near a destroyer class ship. Fourteen Navy helicopter pilots were tested in a within subjects, factorial combination of fixed base, moving base, and g-seat conditions where delays of approximately 66 or 128 milliseconds existed in the simulator's visual display, and the pilots were to hover near a moving or stationary ship. In addition, an

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effort was made to determine the effect a head-up display of aircraft position had on the measures of control.

Best performance was seen with the moving base simulation while poorest control was associated with the fixed-base conditions and in-between performance was measured under the g-seat conditions. The addition of the longer delay uniformly elevated scores, but movement of the ship model had little effect. Also performance was not affected by removal of the head-up display.

A recommendation is made for the configuration of trainers for aircrews of marginally stable vehicles. This is that motion cuing is likely to be useful for flight regimes such as hover, and that currently platform technology is the recommended source of these cues.

PREFACE

This report documents an experiment conducted using a research flight simulator where the aim was to collect data useful for the specification of training devices. In this case, the Visual Motion Simulator at the National Aeronautics and Space Administration's Langley Research Center was used to simulate a hover task similar to those common in training programs for helicopter pilots. To date, little is certain about simulation requirements specific to training devices for helicopter operators, and the present work was performed to support the development of a specification for trainers to be used by aircrews of the LAMPS MK III helicopter.

The Langley Research Center provided both support and expertise for the project. At a meeting of the Technical Advisory Group of the Navy's Visual Technology Research Simulator, James L. Copeland suggested that the NASA simulator would be the device of choice for this effort and support for the work was provided by Roland L. Bowles. The efforts of several people at the Langley Research Center supported both the development and execution of the study; they were George Ficklen, Alton Hall, Eugene Hicks, Jacob Houck, Lemuel Meetze, Robert Spruill, and Steven Wills. In addition to the NASA personnel, Sperry Support Services under contract to the Langley Research Center provided the following people who contributed to the project: Wayne Burge, Wanda Burrest, Lucielle Crittenden, Lane Hardison, Donald Horne, Gary McDaniel, Nevin Oswald, and Thomas Wompler.

John B. Sinacori acted as a consultant during the design phase of the work, providing his expertise on motion systems and the use of motion cues for flight simulation, and he offered many helpful suggestions concerning the final study.

Several Navy personnel were very helpful. LT F. E. Groenert and LT M. D. Wells RN served during the collection of some preliminary data necessary for the definition of experimental conditions and they provided much useful information about helicopter operations. Experiments require individuals willing to perform under various conditions, and this one was supported by helicopter pilots from the Air Test and Evaluation Squadron One (VX-1) stationed at NAS Patuxent River, MD. They adjusted busy schedules to participate and we thank them. They were LT B. H. Brunson, LT W. E. Christman, LCDR J. D. Ellington, LT F. E. Groenert, LT T. W. Kreeger, LCDR R. P. Krulis, LCDR M. J. McNaull, CDR V. L. Onslow, LT R. J. Radeackar, LT H. G. Story, LT R. J. Vernon, LT P. M. Warr, LT M. D. Wells RN, and LT C. E. Wick.

We would like to thank John Landers of the Naval Air Systems Command for his support of this work, and at the Naval Training Equipment Center, Roy E. Perryman and James E. Bishop provided encouragement. Finally several people acted as proofreaders. They were Walter S. Chambers, Stanley C. Collyer, Elizabeth C. W. Ricard, and John B. Sinacori.

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SECTION I

INTRODUCTION

Designers of modern flight simulators have an impressive array of subsystems which can be added to a training device in order to increase the fidelity of the simulation. A basic flight trainer consists of a realistic cockpit and a digital computer to measure the pilot's responses and drive the instruments appropriately. To this is often added a visual display to present the scenes pilots would see when flying. A host of other options is available, mostly for indicating the motions of the simulated aircraft. This includes mounting the cab on a motion platform, including a g-seat and seat shaker, a g-suit, and helmet loader, and developing the appropriate mathematical models to control these subsystems. These pieces of equipment are designed to provide pilots cues of the transitory and steady-state accelerations and/or rotational rates encountered in a vehicle that can move in three dimensions, but they differ in the sort of cues they can provide. G-seats and g-suits can simulate the pressure cues from long-duration accelerations which a motion platform cannot, as the platform is limited in its movement and can produce accelerations only of short duration. It can be useful for providing information about the onset of acceleration though.

This ability of motion platforms to cue the onset of acceleration has made them popular additions to flight simulators, but recently because of their high initial and life-cycle costs, the effectiveness of this equipment has been questioned. For simulations of large commercial or military aircraft, there seems little doubt that a motion platform is a useful adjunct to a simulation, but for smaller, high-performance aircraft, the results of studies have been less clear and a recent Air Force Scientific Advisory Board (1978) concluded that, "Based on the motion/no motion studies and experiments which have been run to date, a convincing case cannot be made for either including or excluding platform motion in flight simulators for tactical fighters." Even fewer data exist on the usefulness of platform motion cuing for vertical take-off and landing (VTOL) or vertical/short take-off and landing (V/STOL) aircraft. Typically these systems are less stable and more responsive to disturbances than are tactical fighters and one might think that such aircraft might provide training situations where the inclusion of a motion platform in a trainer would be warranted. But the data are not definitive and Stapleford (1978) has commented that, " . . . I think it is fair to describe it (the requirements of motion cuing) as more of an organized art than a science. Our knowledge on many aspects of the problem is really quite limited. In general, it is difficult to answer questions such as: is motion needed to simulate this particular task; if motion cues are not provided, how much will the performance be affected; for a given task, how can the motion capabilities of the simulator which is available be best utilized. Any answers will generally be educated guesses which can seldom be supported by hard facts."

There exists a vast literature on motion cuing (see for instance Puig, Harris, and Ricard, 1978 or Hunter, Gundry, and Rolf, 1977 for reviews) from which it is not clear whether motion cues will aid manual control or training in a given situation. Nevertheless, educated guesses can be based on the nature of the flying task, the system being simulated, and the performance characteristics of the motion cuing system. The consensus seems to be that for a motion plat-

form to add fidelity to a simulation of flight and better yet, to increase the effectiveness of a flight training device, the cues it presents must be of a magnitude sufficient to be sensed, they must be in the proper direction, and they should be timely. Quantitative descriptions of the relations between these factors and how they affect piloting control are for the most part not available, forcing designers of training devices to rely on past experience with similar trainers when specifying a new one.

MOTION PLATFORMS AND HELICOPTER SIMULATION

Several studies report data from helicopter simulators where one of the variables studied was cuing from a motion platform. Fedderson (1962) compared hover control in a fixed-base simulator to a similar task flown in a Navy HLT-7 helicopter and showed that when motion cues were added to the simulation they enabled pilots to make the low-amplitude, high-frequency control inputs characteristic of control in the aircraft. His interpretation was that motion cues served to "quicken" the information from a visual display or the cockpit instruments, whichever the pilots were using to control the system. Ringland, Stapleford, and Magdaleno (1971) compared full six degree-of-freedom motion and three degree-of-freedom motion (only the rotational axes) to a fixed base simulation using the task of instrument hover. They found that the three degree-of-freedom cuing produced the best control performance while worst control was seen under the fixed base condition. These results are an interesting demonstration of pilots' ability to use to their advantage the cues available, as under the angular motion condition they could sense pitch and roll attitude without attending to the attitude display. More time could be spent controlling position of the aircraft and better control scores resulted. In the real world, these specific force cues are not present as the vehicle accelerates in the direction it is tipped, and a six degree-of-freedom motion simulation would be considered more realistic. In fact, considerable effort is usually expended to coordinate forward translation and pitch angle, and lateral translation and roll angle in a simulation to eliminate the cues due to the gravity vector.

Parrish, Houck, and Martin (1977) examined motion cuing for helicopter simulation using the Visual Motion Simulator (VMS) at the Langley Research Center. They had pilots fly a slalom course at low altitude (about 75 feet) and low air speed (about 70 knots) while objective measures of the contribution of the motion platform were collected. At the end of each trial, subjective evaluations were obtained from each pilot. Their results were characteristic of many studies of motion cuing; namely that subjectively pilots preferred the moving base condition but that gross measures of performance, like error scores, showed no effect of the added cues. In this case, measures of pilot input activity did show an effect; they controlled the simulator differently when the motion cues were present but not to the extent necessary to produce different system performance.

Because most of the simulation work done on helicopters and V/STOL aircraft had to do with the development of displays or control laws for the aircraft control systems, and because of the paucity of data on the use of motion platforms with simulations of helicopters, we decided to examine the usefulness of motion cuing using a motion platform with known performance. One of the

difficulties of assessing research performed on a variety of devices is the lack of information about the performance of the motion cuing equipment used. Over the years, the research community has acquired platforms manufactured by different companies, at different times, and often the requirements of a particular problem produced a unique configuration of equipment mounted on the platform. There has been some reporting of the characteristics of research devices, and recently the Advisory Group for Aerospace Research and Development (1979) has issued a set of guidelines to enable comparisons across systems. Because so much of the development work on the motion platform of the VMS has been documented, and because of its high performance, we chose to use it for the present work. As only a few studies of motion cuing have been performed using simulations of helicopters, few recommendations for the design of a training device could be made with certainty. Hence this study was designed to examine the role motion cues delivered by either a motion platform or a g-seat may have for the control of helicopter hover.

G-SEATS

Notions of supplementing a motion base with other hardware designed to provide pilots with the cues of aircraft motion have been available for the past two decades, and during the last ten years, hardware has been fabricated and, to some extent, evaluated. The g-seat is a device designed to provide low-frequency information about sustained accelerations of an aircraft by presenting changes of seat pressure to the pilot. Basically, two opposing points of view exist concerning how this should be done. One emphasizes the changes of skin pressure experienced at various levels of acceleration while the other emphasizes the changes of body position. Both of these cuing philosophies can be found in the software which drives g-seats existing today, but to date no resolution is available to indicate which is preferable. Showalter (1978) has presented some data on these two drive philosophies, but the results seemed specific to given maneuvers and pilots, and do not clearly favor one method over the other. Recently, Kron (1980) has presented a nice discussion of the Singer-Link point of view.

Seats for g-cuing were first introduced into military flight simulation by the Air Force when both the Advanced Simulator for Pilot Training (ASPT) and the Simulator for Air-to-Air Combat were fitted with them (Kron, 1975). An extra seat was sent to the NASA Ames Research Center for testing, and the initial analysis (Showalter and Miller, 1978) indicated that the dynamic response of these first generation, Singer-Link seats could be regarded as a first-order system with a 0.50 second time constant preceded by a 80 millisecond transport delay. The response of such a system is a bit sluggish for flight simulation and there have been some efforts to make these seats more responsive (Albery and Hunter, 1978). Another effort attempted to develop a newer, more responsive seat (Albery and Gill, 1978; Kron and Kleinwaks, 1978), and the result is a g-seat with a movable pan and backrest, fewer air bladders, and a 30 millisecond rise-time. This system, although more complicated, is similar in its performance to the second-generation seat developed at the NASA Langley Research Center by Ashworth (1976).

Some data are available concerning the usefulness of the early seats. Irish, Grunzke, Gray, and Waters (1977) showed that the g-seat of the ASPT aided

piloting control during take offs and GCA landings, yet a later study (Irish and Buckland, 1978) did not replicate the g-seat effect on GCA landings nor was it extended to the more demanding segments of initial confidence maneuvers (loops, rolls, etc.). The particular tasks chosen for the studies that used the ASPT may not have been the best ones with which to demonstrate the usefulness of a g-seat as some success has been obtained with simulations of responsive aircraft using tasks which emphasize vertical accelerations. Using the NASA Langley Research Center's Differential Maneuvering Simulator, a fixed base, air-to-air combat device, Ashworth, McKissick, and Martin (1977) showed the g-seat aided pursuit tracking when the task was to track a lead aircraft with an F-14. Here errors were introduced into the pilot's head-up display to cause him to increase or decrease g's in order to acquire the target. These data were extended by McKissick, Ashworth, Parrish, and Martin (1980) who had pilots perform a similar task flying a YF-16. This study used a factorial combination of cues from a motion platform and a g-seat to examine tracking using the VMS. And again, by adding a g-seat, performance was enhanced over that seen with just the fixed-base or moving-base configurations. Few pilots were used in these tests and some confounding resulted because of differences due to the pilots. Clearly though, a g-seat can be arranged to aid control performance and one of the goals of the present work was to examine the tradeability of the effects produced by a g-seat and a motion platform.

VISUAL DISPLAY DELAYS

For some time, delays in control systems have been known to adversely affect manual control, especially when the delay is in the visual feedback channel. The past decade has seen an increase in the number of tasks which simulation-based flight training has been designed to support. These have been visually guided flying tasks where delays in the presentation of a visual scene have occasionally had noticeable effects on performance. Reports by Queijo and Riley (1975), Miller and Riley (1977), and by Riley and Miller (1980) have indicated that simulations of some aircraft are affected more than others by delays in the visual display, and that other things being equal, the effect of a delay is reduced by the presence of cues generated by a motion platform. Such delays are the result of the calculation time necessary to compute a new position for a simulated aircraft to generate a new visual image, or to move the mass of a television probe. Most flight trainers are presently equipped with computer image generation (CIG) visual display systems which when operating at 30 Hz take about 100 milliseconds to generate an updated image, but conventional wisdom is that phase shifts of less than 30^{o} to 45^{o} at 1 Hz (83 - 125 milliseconds) probably will not affect the control of a flight simulation (Ricard and Puig, 1977). Such conclusions were based on simulations of fixed-wing aircraft and there are few guidelines to extrapolate them to more responsive systems like helicopters. A trainer for aircrews of the LAMPS MK III will probably be equipped with a CIG visual system, so for this reason we decided to incorporate visual delay as a variable in this study. Should performance be affected by delays characteristic of those in present day simulators, then clearly tradeoffs between the cost or configuration of processing equipment and performance in the trainer could be expected. In addition, the demonstration of whether or not the effects of various conditions of motion cuing and visual delay are additive would be useful information.

SHIP MOTION

Generally motion cues, especially those from a motion platform, are believed to supply high-frequency information with which pilots can generate a phase lead--particularly in compensatory tracking tasks. Another function they may serve is to enable pilots to differentiate the motion of their aircraft from motion of the world about or below them. The present case is an example of such a situation where, in order to land on a small non-aviation ship, a pilot must first stabilize the helicopter independent of the moving deck below him. Small fore/aft or lateral translations are difficult to detect as the sea about the ship is moving and affords little in the way of landmarks with which to judge these movements. The mean position of the ship must be used to establish a relative position above it and knowledge of aircraft motion can be used to correct errors in this position.

The LAMPS MK III is expected to be deployed (and recovered) in conditions up to and including sea state 5, and a flight trainer equipped with a CIG visual display can easily depict motion of a ship under these conditions. Motion of a ship model was included as a variable in this study to determine if such motion would increase the difficulty of the flying task, - particularly under fixed-base conditions. Models for ship motion exist (Fortenbaugh, 1978, 1979) which would be easy to implement, so moderate ship motion was studied as the documentation of interactions of ship motion with other conditions of motion cuing would be of interest to designers of trainers for helicopter aircrews.

THE PRESENT EXPERIMENT

Current simulations of helicopters have been difficult to control during the final phase of aircraft recovery--the hover and landing--because of delays in the presentation of the visual scene and because of the narrow field-of-view of these displays. Not enough visual context can be provided to enable pilots to notice small fore/aft translations of their aircraft (most trainers are not presently equipped with side windows) and the total visual delay tends to force the pilot-plus-system toward instability.

The present experiment was designed to examine the effects on hover control produced by adding the cues of aircraft motion (from a g-seat or motion platform) to a fixed base simulation. In addition, the effects of a delay characteristic of modern trainers equipped with CIG visual displays were investigated. Finally, the model of a destroyer class ship was made to move or be stationary so that the effects of this manipulation could be determined. The aim was to measure the limits of control performance afforded under these conditions, i.e., how well the device could be controlled was assessed, and no effort was made to examine the acquisition of the control skill.

To this experiment was added a second small experiment to determine the contribution to vehicle control provided by a head-up display (HUD) of aircraft position. This information was added to that required for the VFR hover task and the goal of this evaluation was to assure ourselves that the main results of the study did not depend upon the presence of the HUD.

SECTION II

METHOD

SUBJECTS

The fourteen helicopter pilots used in this study were all volunteers from the Air Test and Evaluation Squadron 1-VX1, stationed at NAS Patuxent River, MD. Fifty-seven percent of them were pilots of the SH-3 helicopter, while the rest flew the SH-2. They had an average of about 8.5 years of experience as military pilots with an average of 1584 hours of rotary-wing flight. More data summarizing the characteristics of this group are presented in Table 1.

TABLE 1. FLIGHT HOURS, YEARS OF SERVICE, AND NUMBER OF SMALL-SHIP LANDINGS

	Flight Hours				
	Total	Fixed-Wing	Rotary-Wing	Years of Service	Small-Ship Landings
Minimum	1000	100	750	5	12
Maximum	4400	1000	3400	19	600
Average	1871.8	294.6	1584.3	8.4	218.9
Std. Deviation	993.9	212.1	849.4	3.9	194.3

EQUIPMENT

The VMS at the Langley Research Center is a general-purpose, two-seat transport cockpit mounted on a motion platform and is equipped with a g-seat and a visual display. For this study, the right-hand seat was configured for helicopter operations by the addition of both a collective and cyclic. The collective of the VMS was a counter-balanced, friction-controlled stick representative of modern helicopter controls, while the two-axis cyclic, manufactured by McFadden Electronics (McFadden and Joas, 1978), was controlled by an analog computer. The rudder pedals were loaded by a hydraulic system coupled to a special-purpose analog computer which, in order to simulate the free-floating pedals of a helicopter, was augmented by the simulation system's digital computer. This created a rudder control system where the pedals would not return to center but would remain in position when force was removed. The control system for these rudder pedals is depicted in Figure 1.

Instrumentation in the cockpit included indicators of altitude, vertical speed, motor RPM, turn and bank, direction and airspeed. An ADAGE AGT 130 graphics processor created a head-up display (HUD) indication of lateral, longitudinal and vertical position which was video mixed with the TV signal used to drive the pilot's visual display.

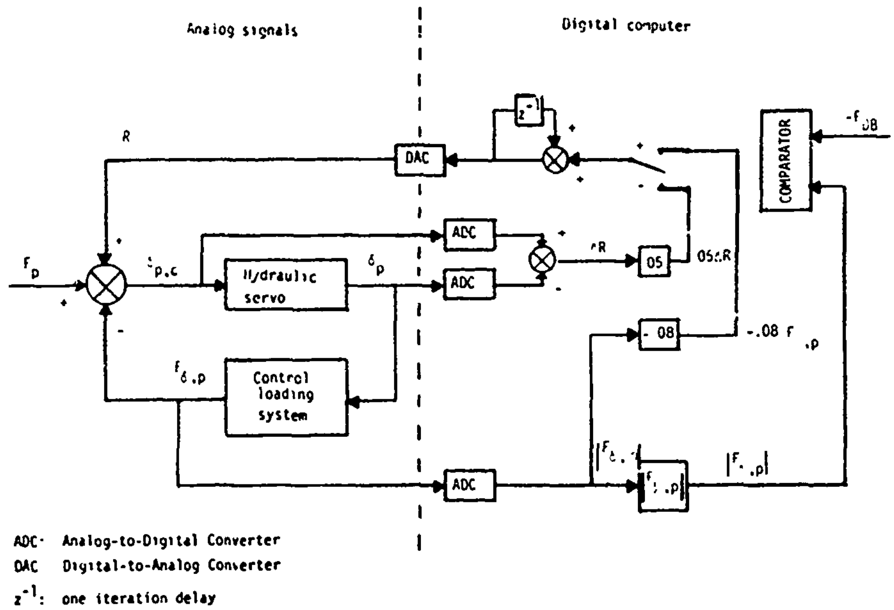

Figure 1. Circuit to Produce Free-Floating Control for Rudder Pedals.

The motion base, g-seat, TV probe, and cockpit instruments of the VMS were all driven by a six degree-of-freedom force and moment model of helicopter flight including a modified single-blade element model of the rotor. This study used the coefficients for a Huey-Cobra (AH-1) with a rate control stability augmentation system used to make control of the system difficult. The model was developed by Houck, Gibson, and Steinmetz (1974) and has been applied to the problems of intercity helicopter operations (Callan, Houck, and DiCarlo, 1974), the evaluation of visual, auditory, and motion cues for helicopter simulation (Parrish, Houck, and Martin, 1977), and the development of performance measurement for display evaluation (North, Stackhouse, and Graffunder, 1979).

The entire simulation was controlled by a Control Data Corporation CYBER 175 computer with associated analog interfacing equipment and control consoles for operators.

MOTION PLATFORM. The motion platform of the VMS is a modified Singer-Link six-post synergistic system with strut extensions of 60 inches. A Bode´ plot of its translation performance is presented in Figure 2. An analysis of its compensated phase characteristic indicates an equivalent steady state

delay on the order of 15 milliseconds. The limits of performance of this system (for single-degree-of-freedom operation) are presented in Table 2, but care should be exercised in interpreting these data as the limits change as the orientation of the synergistic base varies.

TABLE 2. PERFORMANCE LIMITS FOR SINGLE-DEGREE-OF-FREEDOM OPERATION OF THE VMS

Degrees of Freedom	Performance Limits		
	Position	Velocity	Acceleration
Longitudinal, x	Forward 1.245 m Aft 1.219 m	±0.610 m/sec	±0.6g
Lateral, y	Left 1.219 m Right 1.219 m	±0.610 m/sec	±0.6g
Vertical, z	Up 0.991m Down 0.762 m	±0.610 m/sec	±0.8g
Yaw, ψ	$\pm 32^{0}$	$\pm 15^{0}$/sec	$\pm 50^{0}/\mathrm{sec}^{2}$
Pitch, θ	$\pm 30^{0}$	$\pm 15^{0}$/sec	$\pm 50^{0}/\mathrm{sec}^{2}$
Roll, ϕ	$\pm 22^{0}$	$\pm 15^{0}$/sec	$\pm 50^{0}/\mathrm{sec}^{2}$

Note: These values assume a neutral point of 0.6161 m (2.02 ft).

A number of modifications have been made to this system which make it nonstandard. The performance envelope of the platform has been extended and some of the anomalous cues commonly generated by motion platforms have been removed or reduced. First, the hardware filters on each leg were removed. This increased the bandwidth of the leg extension servo system to about 18 radians/second. Then first- and second-order lead compensation was generated to increase the system response. Because acceleration values were not available within the washout calculations for the rotational degrees-of-freedom, a first-order lead was used for these axes. And last, a band reject filter with a notch centered at 32 Hz was applied to each leg to reduce the stepping noise from the system's update rate. These changes

produced the performance labeled "compensated" in Figure 2.

The result of these changes for all axes of control for the motion platform of the VMS yielded a compensated phase characteristic indicating a steady state delay of 15 milliseconds.

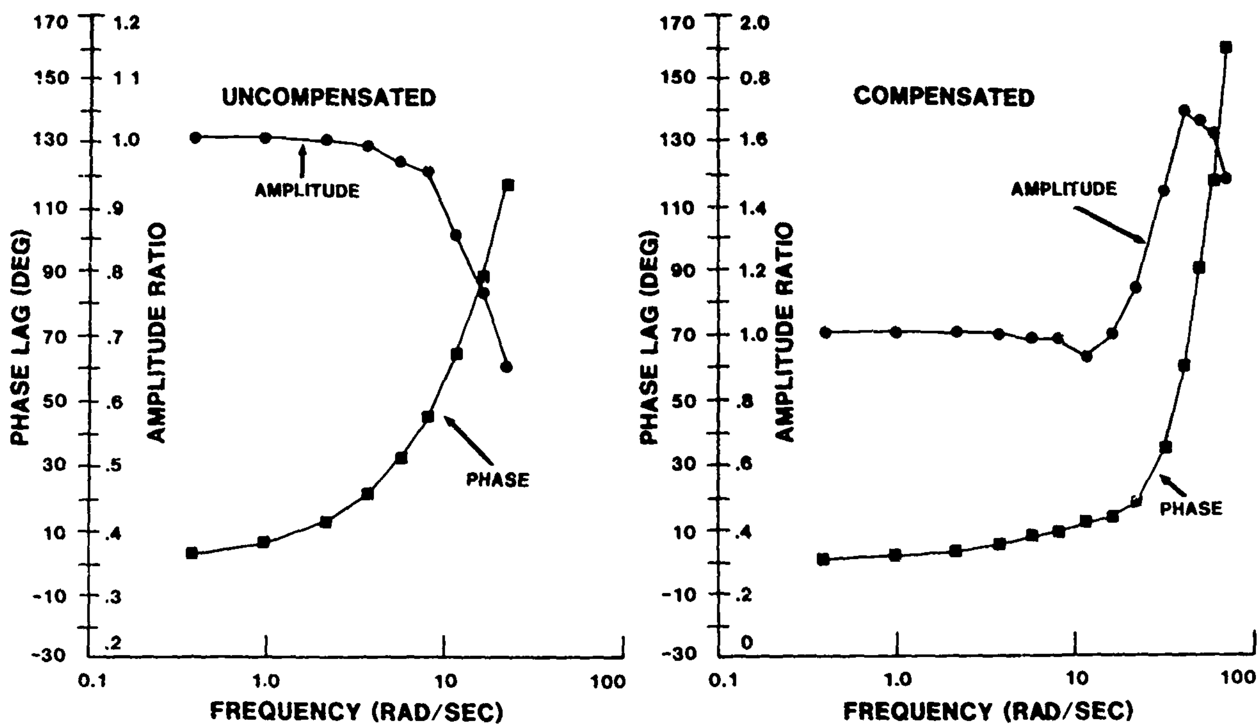

Figure 2. Bode Plot of the Response of the Motion Platform of the VMS.

NOTE: These curves were obtained using a forcing function that was the sum of 12 in-phase sinusoids scaled so that the platform's response would not exceed half of its limit of 0.6g ($\varepsilon\ a_i\ \omega_i^2 = 0.3g$). In addition, a limit of 2.0 inches of peak-to-peak travel was imposed.

Most drive algorithms for flight simulator motion bases produce anomalous cues of acceleration (in the translational axis) or rate (in the pitch/roll rational axes) due mostly to the use of linear high-pass filters to "washout" the change of position of the platform that provides the motion cue for the translation or rotation. On the VMS, these anomalous cues have been significantly attenuated by the use of nonlinear adaptive filters to appropriately

modify the drive signals sent to the platform's legs. Parameters for the adaptive filters are calculated by the method of continuous steepest descent in order to minimize a cost function, and maintain the translational or rotational positions within the motion envelope of the synergistic base. Specific parameters of the nonlinear coordinated adaptive washout used in this study are presented in Table A-1 of Appendix A. The characteristics of these uncoordinated filters are presented in Figure 3. Here the amplitude and phase response of the first-order (for the rotational degrees-of-freedom) and second-order (for the translational degrees-of-freedom) adaptive filters are compared to their linear equivalents, and they show favorable changes of low-frequency gain and phase.

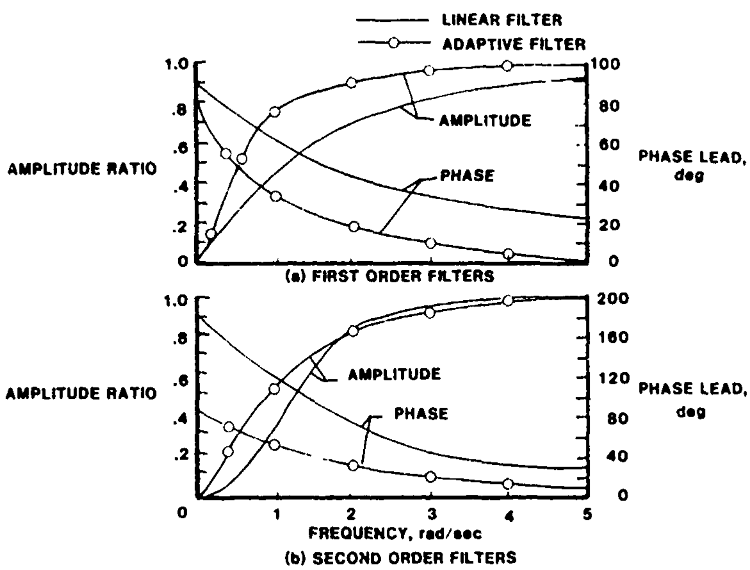

Figure 3. Bode Plots of Filters Used to Produce Coordinated Adaptive Washout.

Part of the implementation of the adaptive filters is an attempt to coordinate translational and rotational cues to appropriately use the gravity vector as a cue. Sustained longitudinal acceleration can only be represented in motion simulation by rotating the pilot and using the gravity vector to supply the cue. As the tilt should be supplied subliminally, a forward/aft translation must be used to cue the acceleration's onset. If only rotation were used, for instance, a "false cue" due to the misalignment of the gravity vector would result. A similar situation exists for roll and sway where a

translation must cue the onset of an acceleration which is then washed-out as a rotation of the platform is used to supply the continuous cue. Both of these techniques are used to coordinate the motion drive signals generated for the VMS. Figure 4 presents a diagram of the system used to condition the signals sent to the motion platform of the simulator.

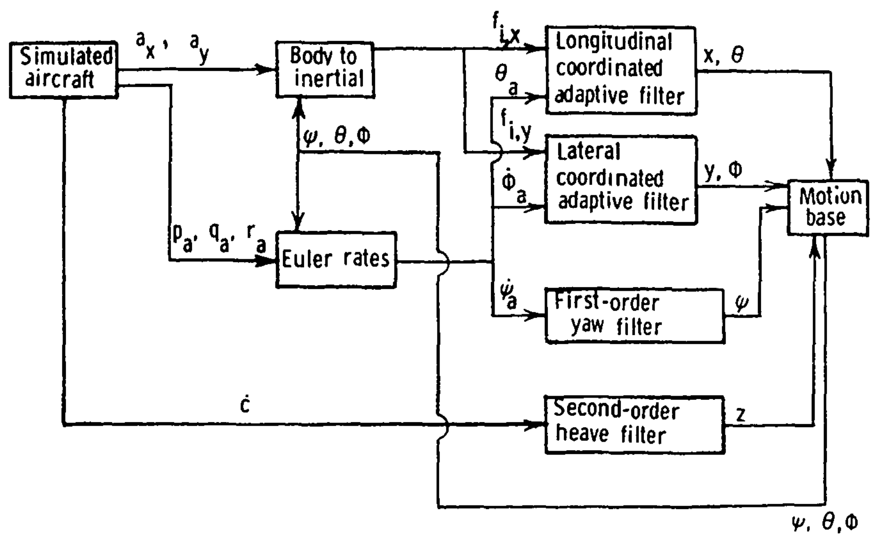

Figure 4. Scheme for Coordinated Adaptive Washout.

The techniques to increase the system's bandwidth and to coordinate drive signals for the legs of the platform, along with their software implementation have been documented in a number of publications. The method of determining the actuator extensions and its software implementation have been discussed by Dieudonne, Parrish, and Bordusch (1972) and Parrish, Dieudonne, and Martin (1973), and a listing of the program and its variables is presented by Martin (1977). The compensation scheme and notch filter for the legs of the motion system are discussed by Parrish, Dieudonne, Martin, and Copeland (1973), and the NASA Langley nonlinear washout scheme has been presented by Parrish and Martin (1975, 1976). Finally, the rules for the adaptive filtering and cue

coordination have been presented by Parrish, Dieudonne, Martin, and Bowles (1973, 1975).

G-SEAT. The g-seat used in this study was a second-generation seat designed and fabricated at the Langley Research Center. The seat pan contains inflatable pads supported by a hard surface. Initially these pads are biased with just enough pressure to support a pilot so that just his two main areas of support, the ischial tuberosities, contact the hard pan. This bias adjusts the "firmness" of the seat. Then as acceleration increases (positive g's develop) air is removed allowing the pilot's weight to compress the bladders and force more of his weight to be supported by the areas about the tuberosities. However, some air is left to prevent a false cue of the seat falling away from the sides of the legs and buttocks. For negative g's, sufficient air is added to the bladders to support the body weight without allowing them to become too firm due to too much pressure. This manner of operation which reproduces the seat actions found during flight also reproduces other related events, such as raising or lowering the body which changes the pilot's eye position and joint angles.

In this seat, the cushions were made of pliable rubber and have four air cells. To allow their differential control, each of the four air cells has its own pressure controller. The air cells are 2.54 cm (1 inch) thick to minimize "following" as the pilot shifts weight and to reduce the seat's response time by lowering the volume of air required for operation. Pressure feedback from transducers located at the air cell is used to provide a linear response for the anti g-suit valves which are equipped with motor driven slugs that control air flow into the bladders. Such a valve provides responsive pressurization and adequate bleed time without the aid of time consuming booster relays and although there is a nonlinear relation between the slug's displacement and output pressure, the feedback forces this response to be linear. Over the range of accelerations experienced by fixed wing, tactical fighter aircraft, this response is shown in Figure 5 and the control system for each seat pad is shown in Figure 6.

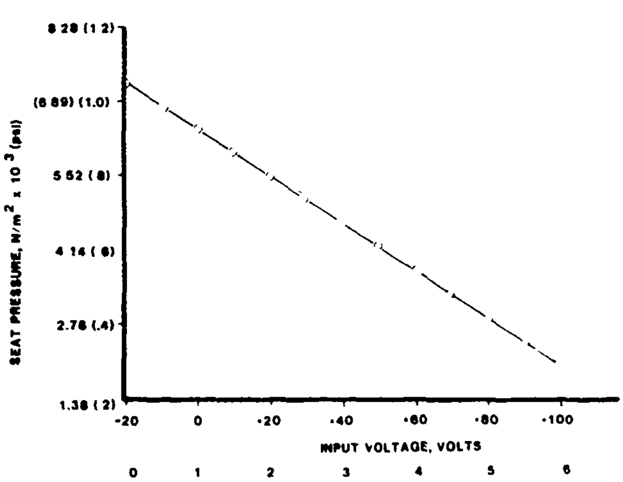

Figure 5. Static Response of G-Seat.

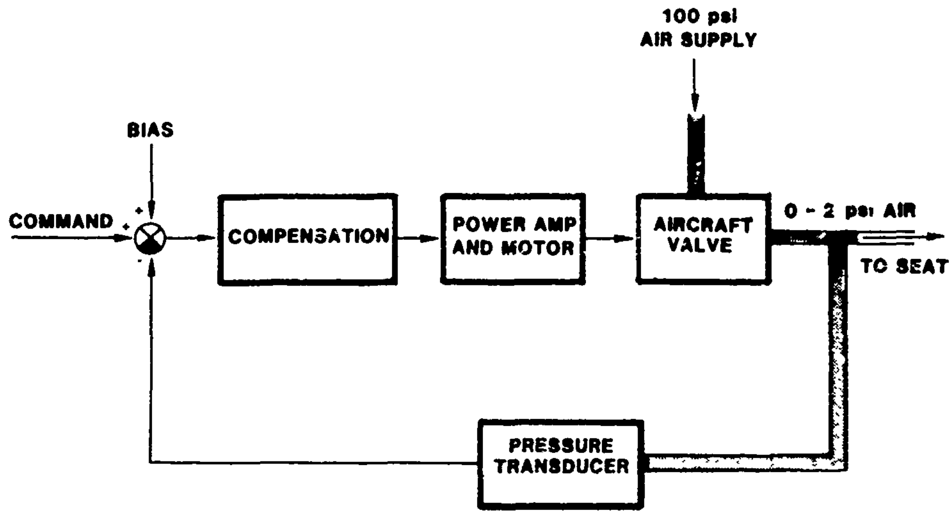

Figure 6. Servo Controller for Seat Compartment.

Ashworth (1976) provides data on the step and sinusoidal responses of the seat that shows it can be considered a 0.45 damped 25 radians/second second-order system over the range of 0 to 8 Hz. This provides a 35 millisecond steady state delay from seat command to seat pressure over the seat's full range of operation, and when the simulator's iteration time (3/2 H) is added to this, it yields a g-seat delay slightly in excess of 80 msec. The step response of the seat pads is shown in Figure 7.

Normally, for simulations of fixed-wing fighter aircraft, the full dynamic range of the seat is scaled from 0 to 6 g with the 1g neutral position biased as a function of the pilot's weight. As helicopters rarely experience accelerations greater than 1.5 to 2g, and as the task selected for this study would involve vertical accelerations well below these levels, the seat was driven to represent pitch and roll accelerations and longitudinal acceleration. Table A-2 of Appendix A presents the drive equations and scaling constants for each of the seat's four cells.

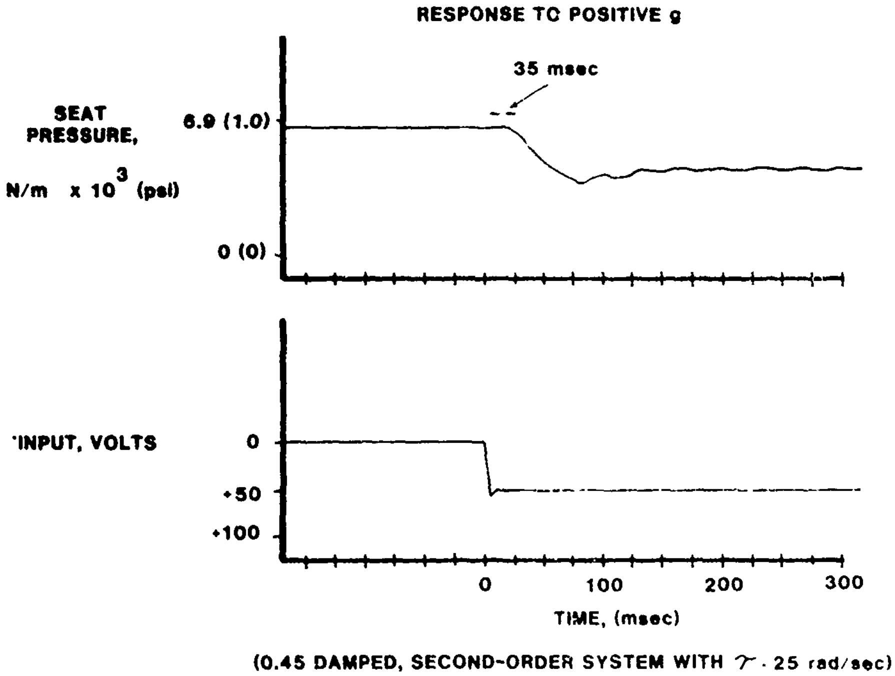

Figure 7. Step Response of G-Seat to a 50 percent Maximum Input.

VISUAL DISPLAY. The VMS is equipped with a Redifon model board and television system to present images of an air field, terrain, and ship model. A beam splitter and television tube present a virtual image 4.17 feet from the pilot's eye with an angular size of 48° horizontal by 36° vertical. This allows an instantaneous field of view of 46° by 26°. The 525 TV line system presents color images at unity magnification with a nominal resolution on the order of 9 minutes of arc. The approximate second-order transfer function for the uncompensated camera transport system is presented by Rollins (1978) and presently shows a steady state delay for the translational channels of 15 milliseconds and a 22 milliseconds delay for the rotational channels.

The model board measures 24' by 60' and displays air fields and terrain at two scalings 1500:1 and 750:1. On the larger scale air field, a helicopter landing area is marked with a Maltese cross to indicate the touchdown point. This area, which allowed a wide range of maneuvers, was used for initial training. For purposes of maintenance, the camera transport system can be driven beyond the perimeter of the board, and it was in this area that a 4' square area was constructed to mount a 380:1 model of a DEG 1052 ship. This model, equipped with a helipad, hangar, and appropriate deck markings, was

mounted on the four cells of an extra g-seat. The model could thus be made to move in the pitch, roll and heave axes. A view of an aircraft carrier (used for the development work of this study) is shown mounted on the g-seat pads in Figure 8. Here can be seen the method of mounting the ship model on the pads.

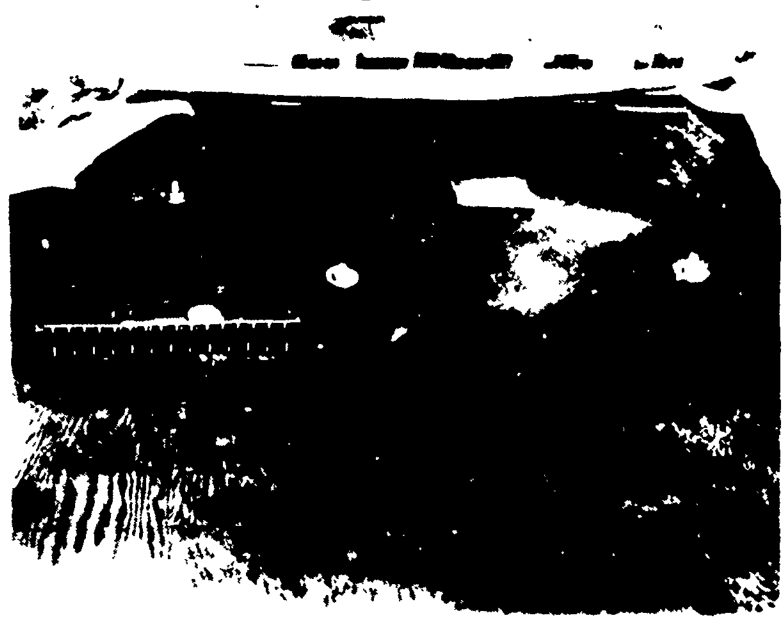

Figure 8. View Showing Mounting of a Ship Model on G-Seat Pads.

The absence of a wide field of view visual display on the VMS makes the determination of altitude and fore/aft translation difficult, so for this reason, a head-up display (HUD) was added to supply position information. A computer graphics display was used to generate x, y, and z-axis scales and these computer generated scales with their circular position "bugs" were video mixed with the image from the model board system and then presented to the pilot on his visual display. Figure 9 presents the image of the destroyer's landing area with the HUD information added. Each scale marking represents 20 feet, and deviation of the bugs from their center

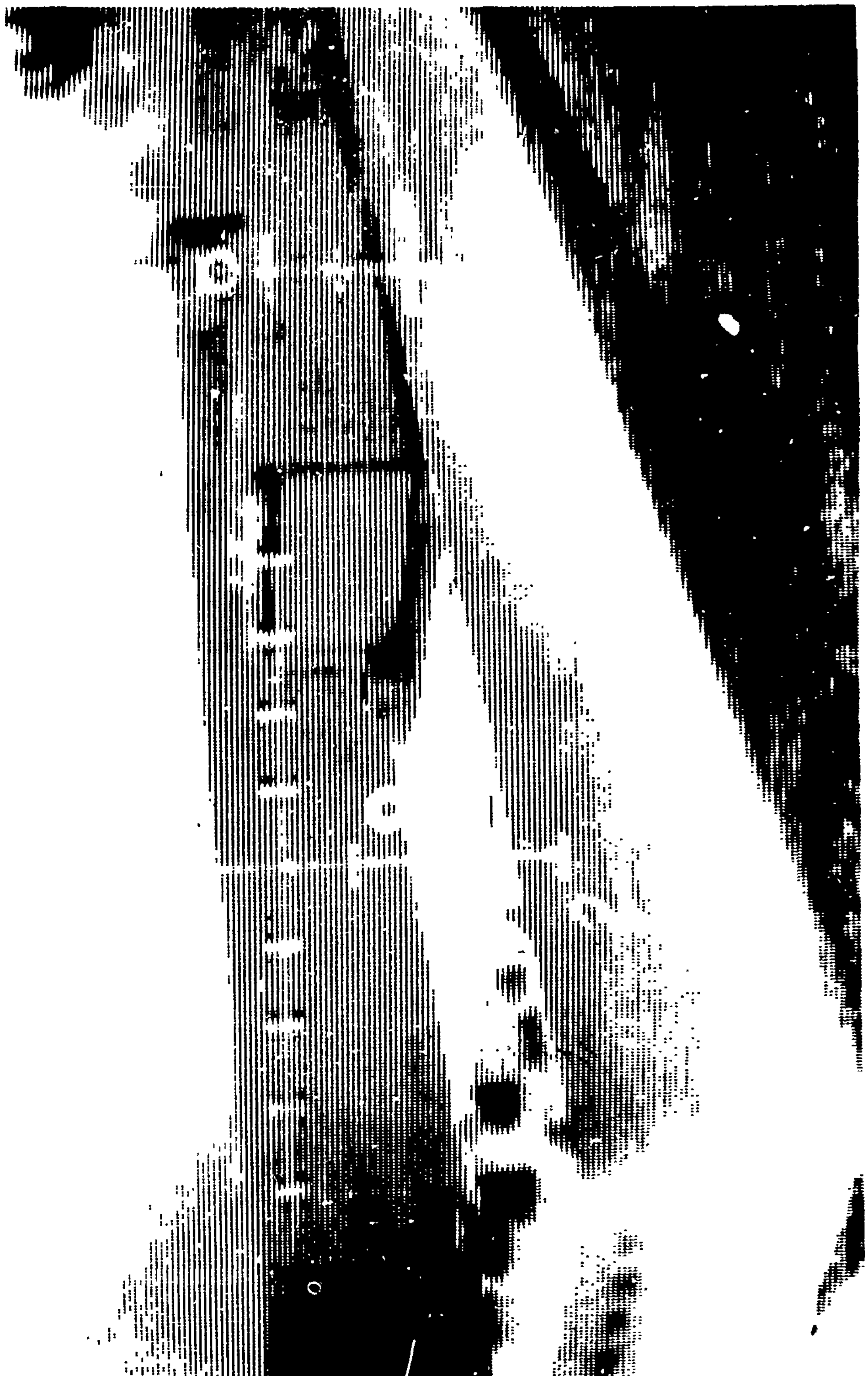

Figure 9. Pilot's display of the landing area including the HUD symbols.

position represents an error of longitudinal, lateral, or vertical position from the desired hover point. During the development work for this experiment, over control was induced when pilots attempted to fly using only the HUD position information (control errors increased by an order of magnitude), and so, for this reason, the brightness of the HUD was decreased to a level barely visible to the pilot. At this level, the presence of the HUD did not affect hover control yet it provided a necessary reference when the pilots wanted it.

AUDITORY CUES. Auditory cues of rotor noise were created by using a general-purpose analog computer to multiply a 100 Hz sine wave by a second half-rectified sine wave of controllable amplitude and frequency. The 100 Hz wave provided a realistic tone, the half-wave rectifying of the second wave provided the desired pulsing, and the variation of the second wave's amplitude and frequency provided the cues of rotor loading. The amplitude and frequency of the second sine wave were calculated digitally every iteration and then were used to control an analog generator. Amplitude was varied as:

$$\text{Percent Full Amplitude} = 20.3|\theta_a - \theta_{trim}| + 0.2|RPM - RPM_{trim}| + 0.002|\dot{h}| + 15.0|\theta_a| + 2.38\ \delta_c$$

where θ_a = aircraft pitch angle in radians, θ_{trim} = -0.13, RPM = rotor revolutions per minute, RPM_{trim} = 290, $\dot{h}$ = rate of change of altitude in m/sec, and δ_c is collective position in percent of full. Pulse frequency of the cue was calculated (in radians/sec) as ω_p = 0.1112 RPM and then compared to the immediate past value. If the difference between them was $\leq$ 0.1, the past value was used as the pulse frequency, if this difference was > 0.1, the new calculated value was used for the pulse frequency.

In addition, this half-rectified sine wave was introduced into the heave channel of the motion platform to simulate vibration levels. Full amplitude produced a peak-to-peak motion of the platform of 5mm.

SHIP MOTION MODEL. Recently the flying environment about DD-963 class ships has been mathematically modeled (Fortenbaugh, 1978, 1979) and these data were used to create the pitching, rolling, and heaving motions for the destroyer model. A sum of four sine waves of frequencies and amplitudes appropriate for a sea state 3 were used to drive the air bladders upon which the model was mounted. Table A-3 of Appendix A presents the drive equations for the seat pads and also presents the amplitudes, frequencies, and phases of the components.

Along with pitching, rolling, and heaving motions, a forward velocity of 15 knots was simulated for the ship by driving the model board system's visual probe with relative longitudinal and lateral position and velocity information. The ship model was thus stationary but the pilot had to fly appropriately in order to maintain his station.

TURBULENCE. To make the control task taxing, atmospheric turbulence was added. Wide-band random numbers were filtered to have an appropriate spectrum and then scaled to a gust amplitude of 2.96 knots (5 feet/sec). This represented

only random disturbances, no ship-related air wake (burble) or ground effects were included in the simulation of rough air.

TASK

Normal helicopter approaches to a destroyer landing pad are made by flying to within four to five miles of the ship and, at that distance, beginning a deceleration and a descent down the glideslope using the glideslope indicator as a reference. The approach is made from aft of the ship until when close; the deck markings and drop lights are used for lineup. When the pilot is close to the ship, the aircraft is maintained at a high hover about level with the top of the hangar until it is stabilized and its forward speed matched to that of the ship. When it appears that motions of the deck will momentarily subside, the landing signal enlisted commands the aircraft forward to the landing area. Here the pilot maintains a low hover (about five to six feet above the flight deck), tracking the deck motion, until he is told to reduce the collective input and the aircraft is landed. Deck motion is normally not tracked during the high hover and the helicopter is held stationary in space even though the visual cues for this position are changing as the ship moves under the aircraft.

There is a need for precise control of a helicopter during the last phase of the approach--from the high hover to the touchdown. For instance, the diameter of the main rotor of the Sikorsky S-70L (the prototype of the LAMPS MK III) is 53'8" and when this craft is centered on the landing area, there are less than four feet of clearance between the rotor and the hangar door. The development of such close tolerances as the helicopter approaches landing is the main reason for using a diagonal approach pattern and for allowing a stabilization period before the craft is flown over the ship. Because we did not want to risk damage to the optical probe of the TV system, a full landing was not simulated. Our task incorporated most of the elements of the high hover in that the top of the hanger was the reference for altitude, deck markings were visible for lineup, and there was enough visual context to roughly judge distance from the ship. Our hover position was chosen to be 50 feet from the ship in line with a diagonal deck marking and at a mean height of 20 feet above the flight deck. Figure 9 presents the pilot's visual scene when he was roughly in that position.

Because of drift in the model board system, the zero-point of the HUD was set to the starting position of each trial and when this starting point indicated significant drift, the aircraft was realigned with the visual references before a trial was begun.

EXPERIMENTAL VARIABLES

Our main question was, for the task of helicopter hover, to determine the usefulness of the cues of aircraft motion which can be provided by a motion platform or a g-seat. To this end, the variable of simulated motion was represented by three conditions: operating the VMS in a fixed base mode (FB), adding the g-seat to the FB condition (G), or running the simulation in a moving base mode (MB). Some studies have factorially combined cuing from a g-seat (on or off) with MB and FB conditions (McKissick, Ashworth, and Parrish, 19[illegible], for instance) to examine the additivity of the effects of each piece of

equipment, but that was not our purpose here. Our aim was to determine how tradable were the enhancements to performance created by the use of a g-seat or motion platform, and to that end only the three conditions of motion cuing were used.

To the motion cuing variable was added that of a visual delay in the simulation. With the advent of computer image generation (CIG), calculation delays produced by this equipment have become a source of concern and while there is an ongoing effort to define minimum allowable delays (Queijo and Riley, 1975; and Miller and Riley, 1977) and compensation for them (Ricard and Harris, 1980), there are no data on control systems as unstable and demanding as responsive helicopters. It is quite likely that a trainer for the LAMPS MK III system will use some form of a CIG visual display, so to provide data on the problems of control that might be expected with that device, a visual transport delay was added to our simulation. The delays and dynamic lags of the various simulation subsystems of the VMS are depicted in Figure 10. The average delay for the presentation of its visual scene is approximately 66 msec and by placing the calculated positions of the simulated aircraft in a pushdown list, an added visual delay of 62.5 msec could be added. This produced a maximum total delay for the visual channel of about 128.5 msec, a value characteristic of modern flight trainers equipped with CIG visual displays. Two conditions of delay were examined, the present capability of the VMS shown in Figure 10 and one with the longer visual delay added.

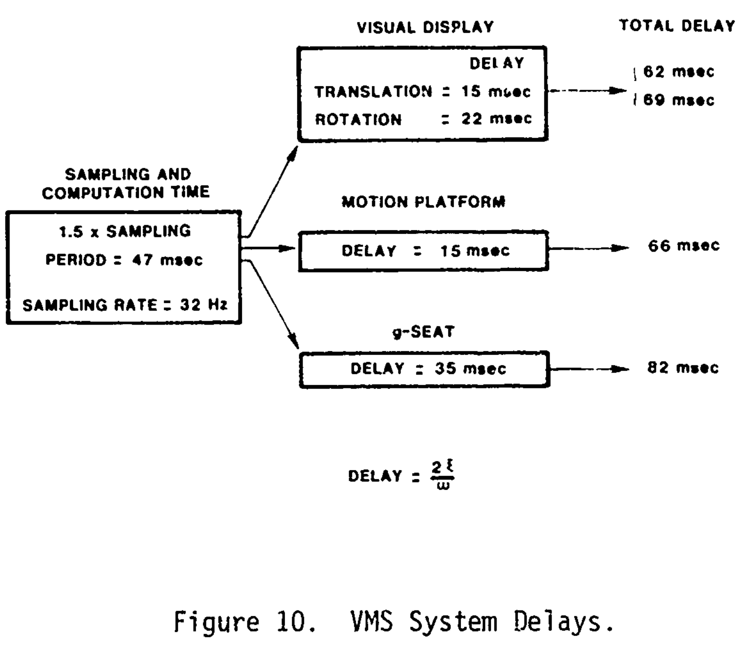

Figure 10. VMS System Delays.

Last, we anticipated that a situation where motion cues would be most helpful in a helicopter simulator would be during ship landing in high sea states where, for a while at least, the pilot's task is to maintain a relative position above the heaving deck. This task of maintaining a mean position without tracking the ship's motion requires information which allows the pilot to separate motions of the ship from motion of his aircraft. Most of the visual scene provides only relative information and we expected that the addition of motion cues from the platform would allow pilots to separate these motions and better maintain the hover position. For this reason the simulation was operated with the ship model both moving and fixed.

PERFORMANCE MEASUREMENT

Three sets of measures were collected to assess the performance of the hovering task. These were system errors, plant states, and pilot control inputs. Using a ship-reference system, the lateral position of the helicopter (y), its bow/stern position (x) and its altitude (z) were sampled 32 times per second and rms values of each measure were accumulated. A radial or vector combination of these errors, $(x^2 + y^2 + z^2)^{\frac{1}{2}}$, was also calculated and accumulated. Plant states were the instantaneous pitch and roll angles of the helicopter; these also were squared and summed. The other rotational degree-of-freedom of the aircraft, its yaw angle, was felt to vary too slowly to be a sensitive measure for the purposes of this work and was not sampled. Last, rms values of the pitch and roll inputs to the cyclic were obtained as well as the rms movements of the rudder pedals. Collective inputs were also measured but, as there was no null position for the collective (its mean value was non-zero), these observations were calculated as a standard deviation.

DESIGN

Three conditions of motion cuing, two system delays and two conditions of ship motion were factorially combined to form a within-subjects, design of 12 experimental conditions. Each of our twelve subjects received a different order of the testing conditions, and these orders were chosen to balance sequential effects during the experiment. Five observations were taken of performance under each condition so that an analysis could partial the effects due to the three experimental variables as well as those due to pilots and to replications. The replications of performance under a given condition were taken sequentially, i.e. performance for a given combination of levels was observed for at least five trials before the conditions were changed. Occasionally, a trial was aborted when for one reason or another performance was atypical (usually very poor). When this happened, that particular trial was restarted immediately.

At the end of the main experiment, two additional subjects were tested without the HUD information added to their visual display. This testing used the ordering of conditions of the previous two subjects so that a comparison could be made of performance with only the image from the TV probe and with the HUD information added.

SECTION III

RESULTS

The investigation was conducted in two parts; a main experiment that examined the effects of the conditions of motion cuing, movement of the ship model, and visual system delays, and a smaller experiment designed to explore the contribution of the HUD to the results of the main experiment. These results will be described separately. Some preliminary data were collected prior to this main experiment and these were described by Parrish (1980).

THE MAIN EXPERIMENT

The data collected in the full factorial experiment were analyzed using univariate analyses of variance for each measure. In these analyses, the effects due to replications (Reps) and pilots (P) were separated from those of the main variables of Motion cuing (M), visual delays (D), and ship motion (S). Table 3 presents a summary of these results. They will be described in detail, dealing first with those involving the error measures, then with the plant states, and finally with the measures of pilot control input, and then they all will be summarized. Appendix B presents the tables for all of these analyses.

TABLE 3. RESULTS OF UNIVARIATE ANALYSES OF VARIANCE

	SYSTEM ERROR				PLANT STATES		CONTROL INPUTS			
					AIRCRAFT		CYCLIC			
SOURCE OF VARIANCE	Y	X	ALT	VECTOR	ROLL	PITCH	PITCH	ROLL	RUDDER	COLLECTIVE
REPS	••			••				••		
P	•••	•••	•••	•••	•••	•••	•••	•••	•••	•••
S						•			•	
PxS					••		•••	•••	•••	•••
D	•••	•••	•••	•••	•••	••	•••	•••	•••	•••
PxD	•••	•••	•••	•••	••	•••	•••	•••	•••	•••
SxD	••	••		••						•
PxSxD		•			•		•••	•••	•••	•••
M	•••	•••	•••	•••	•••		•••	•••		
PxM	•••	•••	•	•••	••	•••	•••	•••	•••	•••
SxM			•							••
PxSxM	•	••		••	•••	•••	••	•••		•
DxM							•			
PxDxM							••	••	•••	••
SxDxM	•							•••	•	
PxSxDxM		•	•		•	••	•••	•••	•••	•••

REPS = REPLICATIONS, P = PILOTS, S = SHIP MOTION, D = DELAY, AND M = MOTION CONDITIONS. • = $p < .05$, •• = $p < .01$, ••• = $p < .001$.

ERROR MEASURES. The rms deviations from the desired hover point (the hover point was moving at a constant forward speed but was not affected by pitch, roll, or heave of the deck) were measured in a ship axis system with x as the bow/stern axis and with y normal to the ship's heading.

Replicates. The replicate factor was determined to be a significant source of variance in the ship lateral direction error term. This effect carried over into the vector error measure. Further examination of this factor revealed a larger average error during the first trial of a condition with subsequent trials being performed at a constant level of error. Figure 11 presents performance as a function of trial number (1 to 5) averaged over all conditions (the means ± their associated standard deviations are shown in this and similar figures). Although each pilot was provided with several practice trials at each new condition, apparently our practice period was not quite long enough even though the replicate factor had no effect for the bow/stern and altitude errors. In any event, this source of variance was isolated from the analysis of other factors.

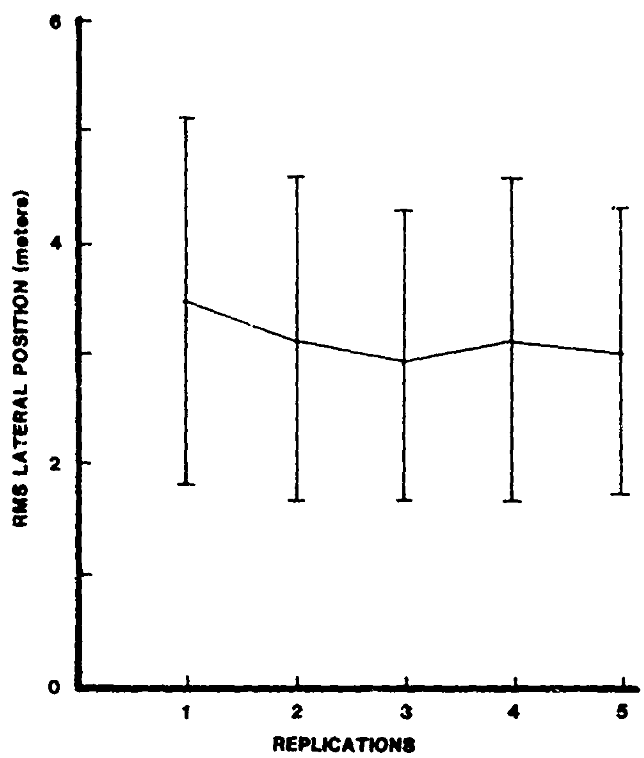

Figure 11. Lateral Position as a Function of Replications.

Pilots. The pilots factor was significant for all of the error measures, as had been expected, and this source of variability also was isolated from the rest of the analyses.

Ship Movement. The movement of the ship model did ,ot significantly affect any of the error measures, nor was its interaction with pilots significant. Thus hover performance as measured by these error measures appears to be independent of ship movement for all pilots. However, ship movement did have a significant influence on the effect produced by the visual delay variable as the ship movement by delay interaction was significant for all but the altitude error. This result will be discussed under the delay factor. A third order interaction involving ship movement was also significant for the same error terms. This interaction, pilots by ship movement by motion cuing, will be discussed under the motion factor.

Visual Delay. All of the error measures were significantly higher during the longer visual display delay when performance was averaged over all of the other factors. However, two of the second order interactions involving the delay variable (pilots by delay, and ship movement by delay) were also significant. Two of the pilots consistently produced better performance on all of the error measures under the longer delay condition, eight pilots showed better performance with the shorter delay, and two pilots appeared insensitive to the levels of delay we used. Although it was expected that an individual's sensitivity to delay would vary, it was surprising to find two pilots who flew better with the longer delay, especially with the degree of consistency shown by these analyses.

The effect of visual delay was more pronounced for the case of no ship movement. This was revealed by the significance of the ship movement by delay interaction shown in Figure 12 for the vector error measure. A third order interaction (pilots by ship motion by delay) was not consistently significant for all of the error scores indicating that the pilots' sensitivity to delays was not affected by movement of the ship model nor did the pronounced effect of visual delay for the ship movement off condition vary significantly from pilot to pilot.

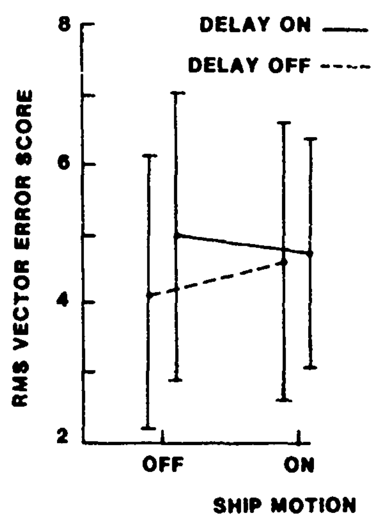

Figure 12. Vector Error Score as a Function of Ship Movement and Visual Delay.

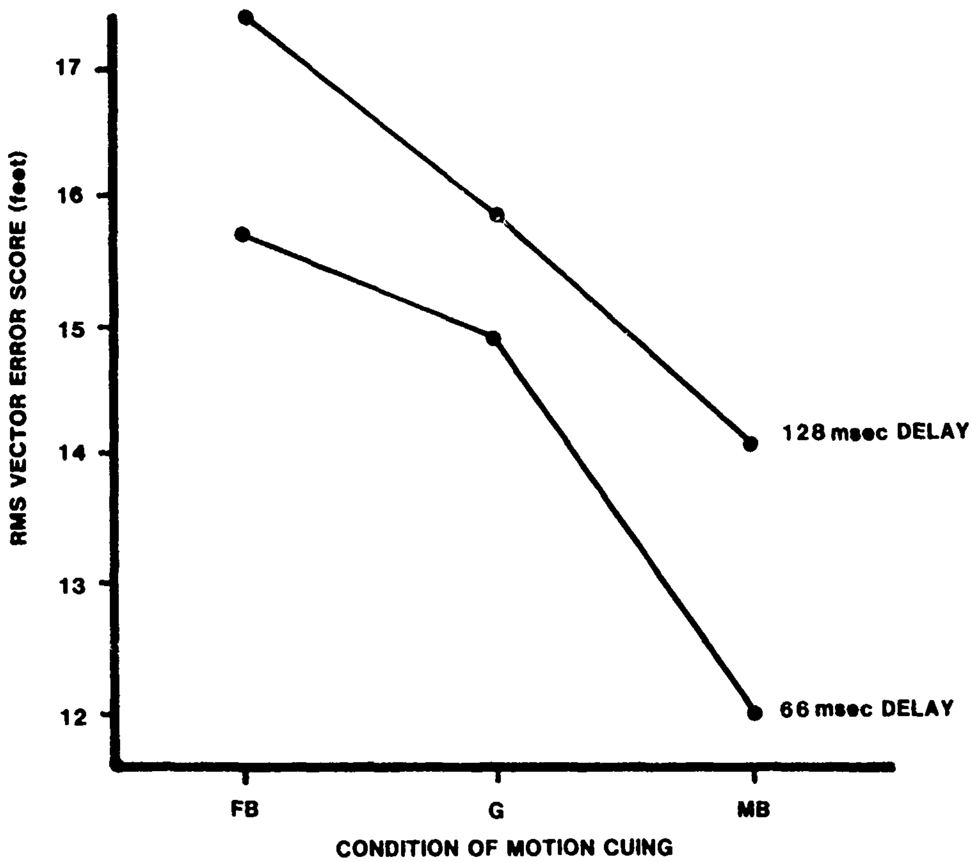

Figure 13. Vector Error Score Averaged Over Conditions of Ship Motion.

Motion. The conditions of motion cuing produced a significant effect on all of the error scores, and the trends in the x, y, and h position errors were almost identical to those shown in Figure 13 for the vector combination score. For this composite measure, error under the fixed base condition was higher than under the g-seat condition which was higher than under the moving base condition. The pilots by motion interaction term was also significant, indicating that the effect of motion cuing varied from pilot to pilot. Examination of these scores indicated that occasionally a pilot achieved better performance under fixed base conditions than under g-seat conditions, but such occurrences were few. Performance under the moving base conditions was always better.

A ship movement by motion cuing interaction was significant for the altitude error score and this interaction is illustrated in Figure 14. As

depicted in that figure, the altitude error score was relatively insensitive to ship motion off conditions except when the g-seat was activated.

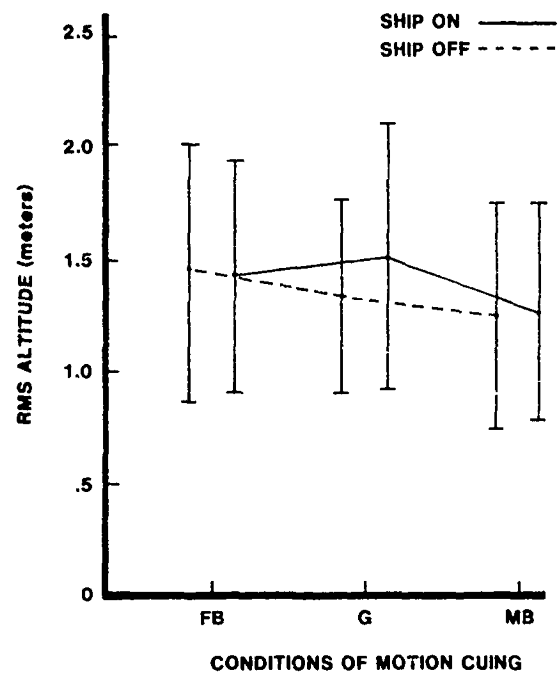

Figure 14. RMS Altitude as a Function of Ship Motion and Conditions of Cuing.

Also found was a significant third order interaction (pilots by ship motion by motion cuing) which indicated that the significant second-order, pilot by motion cuing interaction varies with ship movement. This was caused by some pilots interchanging their better performance between the fixed base and g-seat conditions dependent upon whether the ship motion was on or off.

Other Factors. None of the other interaction terms were considered to be consistently significant. However, this finding is in itself interesting with regard to the delay by motion cuing term (Figure 13). Some preliminary data indicated such an interaction and these results show none. The effect of the conditions of motion cuing is independent of that produced by changing visual system delays, i.e. the effects of these variables are additive.

PLANT STATES. The rms values of the helicopter pitch and roll angles were also analyzed, and generally the results for these measures parallel those for the error scores, with larger rms values for pitch and roll angles accompanying larger errors.

Replicates. No effect of replication was seen in the plant state measures.

Pilots. Both measures of plant state showed a significant effect of pilots, indicating that they differed in the average level of response that they caused the system to produce.

Ship Movement. Unlike the data for the error scores, the ship movement variable produced a significant effect on the pitch rms with higher rms levels for the conditions of ship movement on. A pilot by ship movement interaction in the roll rms measure indicated that this effect of ship movement varied across pilots. Roll rms error was higher for the moving ship conditions for most pilots (seven pilots used higher roll levels for the ship-on condition while four produced less roll activity and one appeared insensitive to ship motion).

Visual Delay. The effects of visual delay on the plant state measures were almost identical to the results discussed for the position errors. Higher rms levels of pitch and roll angles accompanied the longer visual delay for ten pilots, and the two who performed consistently better under the long delay conditions also consistently had higher levels of pitch and roll activity for the long delay cases.

Motion. The conditions of motion cuing produced a significant effect on the roll but not the pitch rms activity. This is illustrated in Figure 15. While the rms pitch measure did not reveal the motion cuing conditions as a main effect, there was a pilot by motion condition interaction indicating that some pilots did cause more pitch activity than others. For both the pitch and roll activity scores, examination of the data indicated that most pilots consistently used lower rms levels for the moving base condition, followed by higher levels for the g-seat condition, with the highest levels seen in the fixed base conditions.

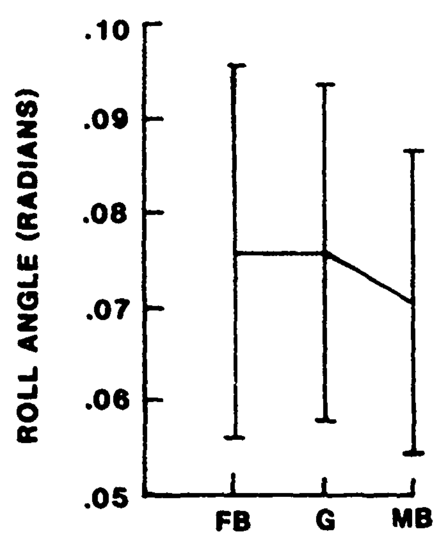

Figure 15. RMS Roll Angle as a Function of Motion Cuing Conditions.

The pilots by ship movement by motion cuing interaction seen in the error scores also was significant for the measures of plant state, indicating that the variability of the motion effect changed across pilots with the conditions of ship movement for these measures also.

Other Factors. Of the other interaction terms, none were considered consistently significant. Again the lack of significance for a delay by motion cuing interaction underscores the independence of these factors as indicated by the measures of aircraft position. The effects of visual delay and the conditions of motion cuing were also additive for the measures of aircraft attitude.

CONTROL INPUTS. Fore/aft (pitch) and lateral (roll) movements of the cyclic, movements of the rudder pedals, and movements of the collective were all measured about their trimmed positions. There was a non-zero trimmed position for the collective, so rather than an rms value, this measure was calculated as a standard deviation.

Replicates. The replicates factor was significant for only the cyclic roll measure. Lateral movements of the cyclic were typically low during the initial exposure to a new condition.

Pilots. Pilots were a significant source of variance for all of these measures. They used different levels of all of the inputs.

Ship Movement. Rudder activity was higher for the moving ship condition, as indicated by the significance of the main effect for this measure. Other control activity measures were also higher for the ship movement condition for most pilots indicated by the significant pilots by ship motion interactions. Seven of the pilots displayed higher control activity during the ship movement conditions, four of the others displayed lower levels of control across conditions of ship movement. Generally, these were the same groups of pilots which were discussed in the analysis of the plant state measures for the ship movement factor.

Visual Delay. The analysis of the main effect of delay and its interactions parallels the results of the analyses for plant states. Typically more control movement was used during the long delay case with the previously noted exception of the two unusual pilots who performed better under the long delay. However, in the case of the measures of control input, not only is the pilot by delay interaction significant because of these two pilots, but the third order term (pilots by delay by motion cuing) also is significant. These two pilots used much less control activity (pitch, roll, rudder, and collective input) for the longer delay case with the g-seat on. The fixed and moving base conditions did not show such a pronounced reduction of control activity during the long delay. The second order interaction of delay by motion cuing conditions is presented in Figure 16 where less cyclic pitch-axis activity is seen during the long delay and the greatest difference due to delay is seen under the fixed base motion condition.

A ship movement by delay interaction was significant for the collective input measure, and this delay effect was most pronounced for the ship movement

off condition, as was the case for the measures of position error. This result can be seen by comparing Figure 17 to Figure 14.

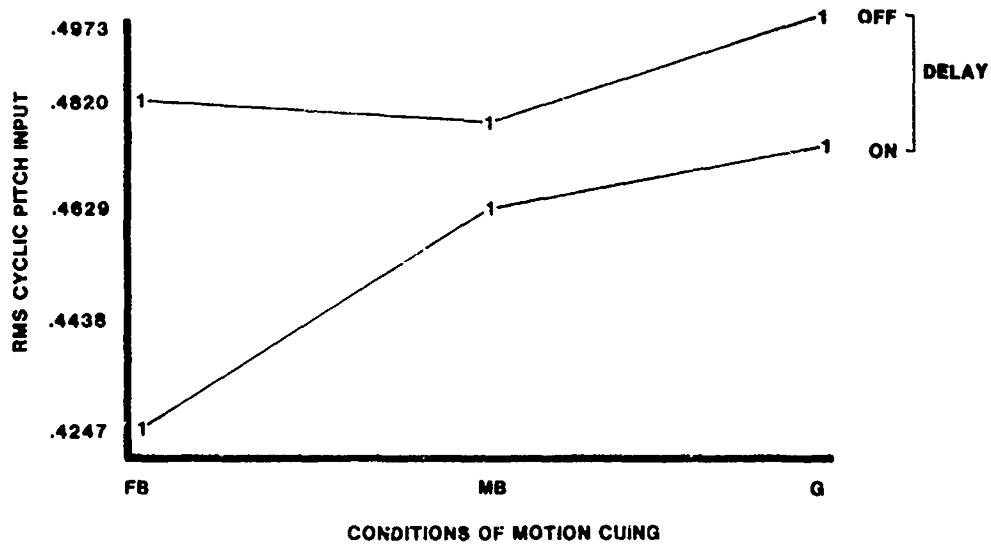

Figure 16. Fore/Aft Cyclic Movements as a Function of Ship Motion and Motion Cuing.

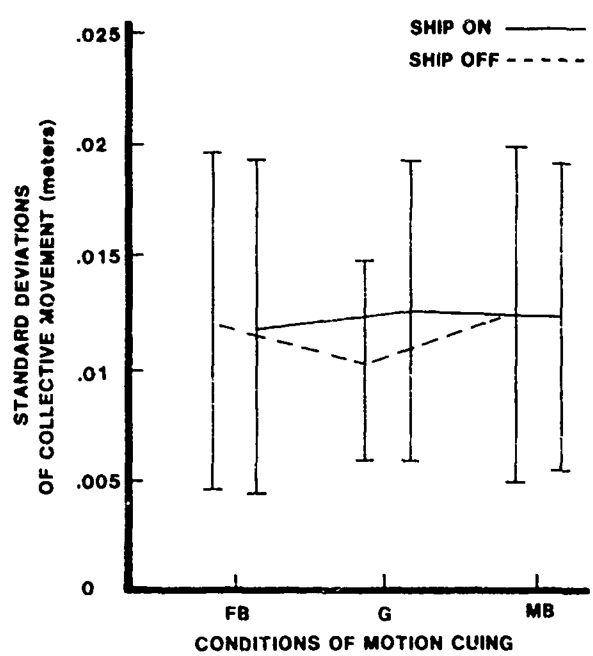

Figure 17. Collective Movement as a Function of Ship Motion and Motion Cuing.

Motion. The main effect of motion cuing conditions was quite significant for the rms cyclic pitch and roll inputs. The least pitch activity occurred under the fixed base condition, this increased for the moving base condition, and was highest for the g-seat condition while a slightly different pattern was seen in the roll measures. Here the levels of roll activity were comparable for the fixed base and g-seat conditions, but there was less roll activity during the moving base condition. All measures of control input displayed a significant pilots by motion cuing interaction indicating differences among pilots in the levels of control activity under the various motion cuing conditions. Most pilots used significantly more rudder and collective input when the motion platform was operating. Generally control with the g-seat more resembled that seen under moving base conditions than under fixed base conditions.

The interaction of ship movement and motion conditions was significant for the collective input, a result that parallels the result for altitude error discussed previously. That these results correlate is not surprising as the collective controls altitude (other things being equal), and the results can be seen in Figures 14 and 17. The g-seat condition appears to be the only condition of motion cuing sensitive to the ship motion factor, for these measures. A third order interaction (pilots by ship movement by motion cuing) was significant for both pitch and roll cyclic inputs. Thus the pilots by motion cuing effect discussed earlier is dependent on the presence of movement of the ship model.

Other Factors. A pilots by ship movement by delay interaction was significant for all four measures of control input, but was not significant for any of the plant states of error measures. Because both the pilots by ship movement and pilots by delay interactions also were significant, and the ship movement by delay was, for the most part, not significant, the interpretation is that the pilots by ship motion interaction changes with changes of the delay variable, and that the pilots by delay interaction changes as a function of the condition of ship movement. Last, the fourth order interaction was significant for all four measures indicating that the significant third order interactions vary with the remaining fourth condition.

SUMMARY OF RESULTS. The results previously discussed in detail can be condensed into several distinct points for each of the main factors of the experiment. This draws on the separate analyses of all of the variables measured.

Replicates. For the most part, the practice trials afforded each pilot at the beginning of testing for a new condition were sufficient to allow him to perform each repetition at about the same level of proficiency. Also the use of rest periods between testings appears to have been successful for avoiding fatigue effects. In any event, this source of variability (along with that of pilots) was by design removed from the analysis of other factors.

Pilots. Every measure of performance we used showed differences attributable to pilots. In fact, this was the single largest source of variance in the entire study and was, by design, isolated from the analysis of the other factors.

Ship Movement. Three points concerning the presence or absence of movement of the model ship can be made. First, we should indicate that only the plant states and the measures of control input showed effects of ship motion, and only for a majority of pilots. Usually higher levels of these measures were associated with the presence of ship motion. The second point concerns the influence of ship motion on the effects caused by visual system delay. With the exception of the altitude error, the rms errors of position showed pronounced delay effects for the ship movement off case with smaller effects of delay seen when the model was moving. The plant states did not show this behavior, and with the exception of the measure of collective movement, the measures of control input did not either. Collective input, which to a degree, correlated with altitude error, showed a pronounced effect of delay for the ship motion off case, and one interpretation of this is that the addition of a visual display delay to an easy task (the ship motion off case) has a more measureable effect than when it is added to a hard task (when ship motion is on). The lack of data to indicate that the ship motion on condition really is harder makes this interpretation a bit speculative though.

The final point concerning ship movement concerns the detectability of its effects across conditions of motion cuing. Averaged across the motion conditions, the position error measures show no effect of the presence or absence of ship motion. However, the altitude error and its counterpart control input, collective standard deviation, both showed significant differences for ship movement on or off when the g-seat was operated. This pronounced effect of ship movement during g-seat operation was also indicated but not to a statistically reliable extent in the measure of rudder activity. These g-seat by ship movement effects were confusing as the seat only presented cues for pitch, roll, and fore/aft translation, and not for vertical acceleration. Our pilots may have tried to extract information about vertical accelerations during the seat-on conditions and thereby produced poor altitude control performance.

Visual Delay. There are also three points of interest from the data on the delay variable. First, all of the measures of the experiment showed an effect of delay and in fact, of the main effects, this was the third largest source of variance in the study. Larger errors, higher levels of the plant states, and more control activity were associated with the 128 millisecond delay than with the shorter one. Second, two pilots consistently reversed this trend, using smaller errors, lower plant states, and smaller control inputs for the longer delay, and the reversal of control activity for the delay effect was more pronounced for the g-seat condition for these two pilots. Finally, as mentioned in the summary of ship movement effects, the effect of a delay was more pronounced for the condition of ship motion off. At least this was true for the error measures and the collective activity score. This result was present in the data for all of the pilots although its direction was reversed for the two pilots who showed a reversed preference of visual delays.

Motion. Four points of interest can be extracted from the discussions of the motion cuing factor. First, when data were averaged over all other factors, all but three measures showed an effect of the different cuing conditions with

the moving base condition producing the lowest position error scores, lower roll control activity, and lower roll rms levels that the other two motion conditions. Pitch control input was lowest for the fixed-base conditions. The motion factor represented the second largest main effect source of variance. Second, for the remaining measures (pitch rms, rudder activity, and collective input), the detection of motion cuing effects was dependent upon pilots in that most pilots showed lower pitch rms levels and higher rudder and collective activity under the moving base conditions, but these results appeared as pilot interactions. The third point concerns the variability of pilots within the different cuing conditions and its dependence upon the ship movement variable. Most of the pilots interchanged the ordering of their fixed base and g-seat performances as the ship movement was turned on or off, however, the g-seat performance was not necessarily better than fixed base performance for the ship movement off condition. Finally, when the g-seat was operational and ship movement was absent, all pilots used less collective input than for any other set of conditions. Other measures did not show this effect, nor were the moving base and fixed base performances different when the ship motion was on or off.

Size of Effects. Eta squared, a measure of the variability accounted for by a factor, can be calculated for any of the analyses from the tables in Appendix B, but here we would like to indicate the size of some of the sources of variance. First, averaged over all of the measures, the error mean square accounted for almost 43 percent of the variances. This was by a wide margin the largest single source of variance in the study. Pilots accounted for an average of almost 29 percent of the variance, and these two sources produced almost three quarters of the variability seen in the experiment. The experimental variables (their main effects and their interactions) all represented rather small amounts of the total variance even though the effects were consistent and sometimes sizeable. Using the data from the analysis of the vector error measure for comparability, motion cuing accounted for about 5 percent of the variance of this measure while visual delay accounted for about 1.5 percent. If these main effects are combined with their first-order interactions with pilots, they account for about 12.5 percent and 5.1 percent respectively. While these are not large sources of variance, performance under the moving base condition represented almost a 22 percent reduction of error with respect to average performance under the fixed base condition. The significant difference between the g-seat condition and the fixed base one represented a 5.5 percent reduction of the vector score, and the short delay reduced the error seen under the long delay by almost 10 percent.

THE HUD EXPERIMENT

In order to evaluate how the HUD might have affected the results of the main experiment, the last two pilots we tested flew the twelve experimental conditions without the superimposed computer graphics display. These two were trained in the same manner as the previous twelve, but without the HUD, and then were tested on the same sequences of conditions as the last two of the main experiment. They had the same familiarization runs at each condition as the regular pilots, and the only way their testing differed was by the absence of the HUD.

Data from this experiment were analyzed in two ways. A univariate analysis of variance was performed on the vector error scores of all fourteen subjects, and the mean squared error term from that analysis was used for a Newman-Keuls analysis to detect differences among the HUD and non-HUD pilots (assuming that differences due to the HUD would be reflected in this manner). Second, a brief analysis was performed on the data from the two non-HUD pilots.

THE FOURTEEN-PILOT ANALYSIS. An analysis of variance was performed on the average vector error scores of all fourteen pilots, and not surprisingly, no changes were found in the statistical significance of any of the results of the previous analyses. The Newman-Keuls test yielded the results shown in Table 4. As can be seen in that table, the two pilots who flew without the HUD produced error scores equal to or better than those achieved by most of the pilots in the main experiment. The non-HUD pilots ranked 4th and 7th out of fourteen, and these results indicate that the HUD was not a requirement for successful performance. The scene without the HUD provided sufficient information for the small ship landing task.

TABLE 4. RESULTS OF NEWMAN-KEULS TEST

Rank	Pilot Number	Mean Composite Score (Meters)	Groupings+
1	2	2.87	
2	11	3.70	
3	7	3.70	
4	13*	3.79	
5	12	3.79	
6	5	4.02	
7	14*	4.23	
8	8	4.34	
9	1	4.85	
10	4	4.90	
11	10	5.08	
12	9	5.88	
13	3	5.91	
14	6	6.10	

*No HUD Pilots

+Brackets indicate the groups within which there were no significant differences for $p<.05$.

THE TWO-PILOT ANALYSIS. It was not possible to analyze the effect of the HUD on the ship movement, visual delay, and motion cuing factors as we did in the major experiment because the order in which the experimental conditions were flown had a substantial effect in this sub-experiment. While the testing order was balanced in the main experiment, this could not be done for the two pilots in the smaller study. Figures 18 and 19 show the effect of testing order on the

means and standard deviations of the vector error scores of the two non-HUD pilots. Clearly the first four experimental conditions flown by the pilot in Figure 18 are biased by the order in which they were flown, but the pilot of Figure 19 shows no such bias. Figure 20 shows the order effect for all twelve pilots who flew the HUD, and any other effect shown here would have been balanced over the twelve experimental conditions. Because of this pilot by testing order interaction shown by the two non-HUD pilots, and because of the lack of differences in their average performances, no further analyses were performed on their data.

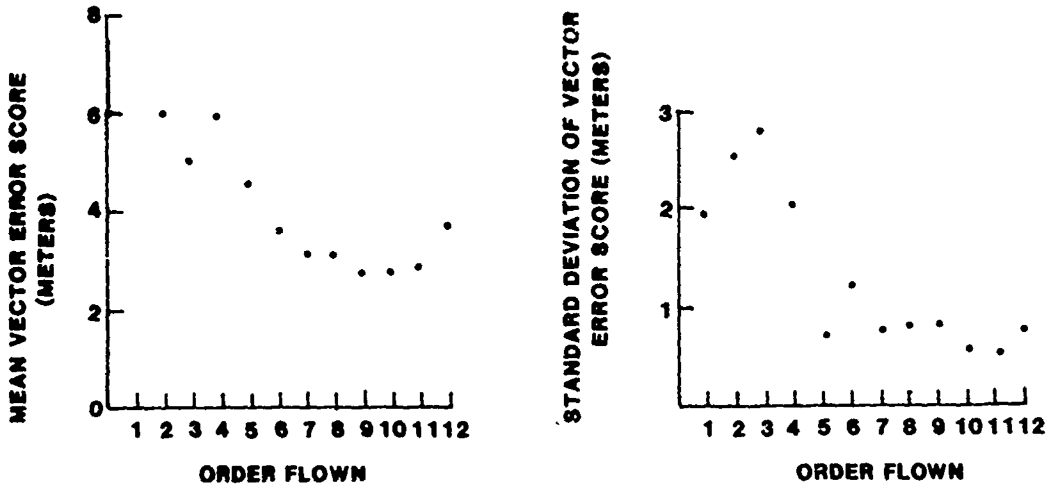

Figure 18. Mean + Standard Deviation of Vector Error Score of Pilot 14 as a Function of Testing Order.

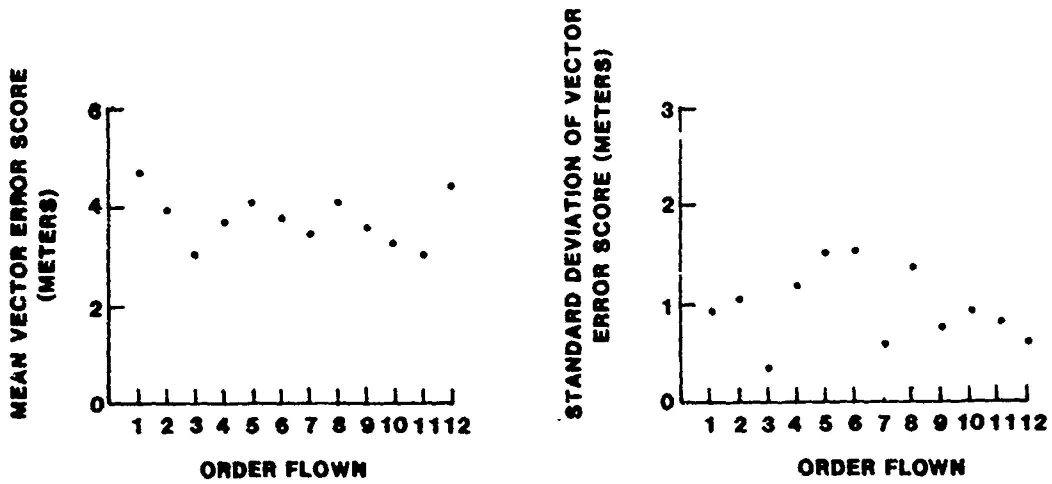

Figure 19. Mean and Standard Deviation of Vector Error Score of Pilot 13 as a Function of Testing Order.

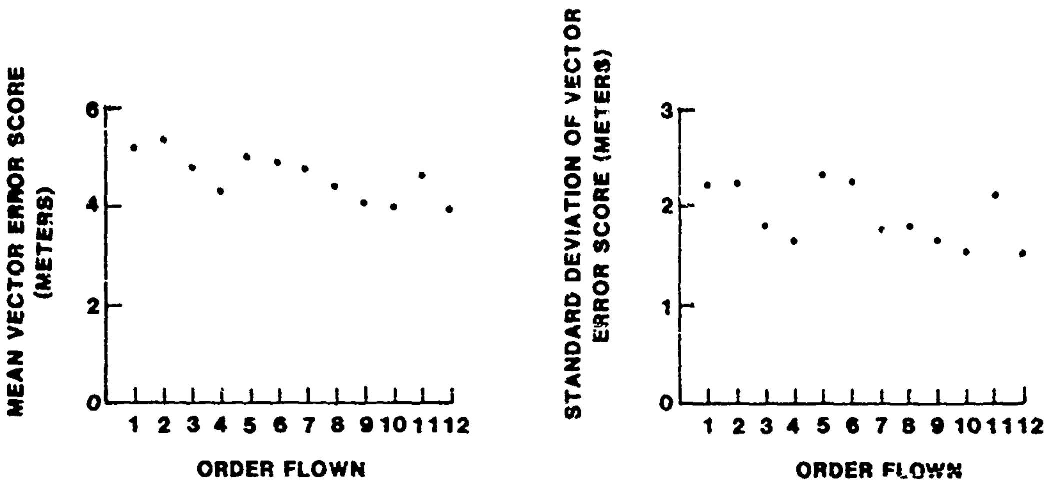

Figure 20. Mean and Standard Deviation of Vector Error Score for all 12 HUD Pilots as a Function of Testing Order.

SECTION IV

DISCUSSION

Often studies of equipment variables produce rather small effects in their dependent measures because users of the equipment, in this case pilots, are quite adaptive and can perform well under a variety of configurations of the equipment. In this case, it was heartening to see that the variables under study produced differences in error scores as well as in the measures of control input and plant state. One would expect measures of pilot input or opinion to be more sensitive than measures of gross error, and indeed, in the study by Parrish, Houck, and Martin (1977), this was the case. Because we did obtain consistent effects in the error measures as well as the others, we feel that the data reflect performance that likely would be seen in training devices for helicopter aircrews.

For completeness, all significant effects were discussed in the results section, but we should indicate that we feel the main results of the study are those depicted in Figure 13. Clear improvements over the fixed base performance were seen when the cues of aircraft motion were added to the simulation. These improvements generally were small for the addition of the g-seat (about a 5 percent reduction of error) and large during the use of the motion platform (over a 20 percent reduction), and these improvements probably reflect a number of conditions specific to this study. First, the motion platform of the VMS has undergone several years of improvements over what might be expected for a training device. For instance, the bandwidth of the motion system of the VMS is considerably broader than that of a motion base for a trainer, its update rate is about twice that of current trainers, and its steady state delay is about a quarter of that common in training equipment. The use of a nonlinear adaptive scheme to control washout also can be expected to enhance piloting control when compared to the simplified models of training devices. All of these factors could cause the 22 percent reduction of error to be specific to the motion system of the VMS, and it may not particularly reflect the performance to be expected in a trainer. One of the reasons for using the VMS was to examine the potential a motion platform may have for helicopter simulation, and it should be remembered that changes of performance of this size are related to the particular system used in this study. If it is expected that a trainer for the LAMPS MK III will be used for training situations where the rapid onset of accelerations should need to be cued (landings on small ships in rough air or high sea states or without stability augmencing systems), then consideration should be given to the addition of a motion platform, especially one with a performance envelope similar to that of the VMS.

Although the effects of adding a g-seat were small, the fact that they were consistently present indicates the potential for this motion cuing device for helicopter simulations. Part of the small effect can be accounted for by the short development time used for the software to drive the seat even though the device represents the generation of responsive seats currently being developed. Furthermore, our task did not emphasize the vertical accelerations for which the device seems best suited. In addition, time did not permit the proper effort needed to scale the seat's response for the range of cues to be expected in helicopter operations. Given the lack of development for the

seat's operation in this experiment, the presence of a five percent reduction of error holds promise for g-seats for helicopter simulators. G-seats represent a new technology for helicopter simulation (there are none in present helicopter simulators), and more development of g-seat cuing devices to reduce their lags and determine what cues they should present and perhaps to scale these cues over the range of g's a particular system may experience would undoubtedly improve the performance seen here.

Another encouraging finding was a lack of a motion cuing by visual delay interaction which was manifest in some of the preliminary data. As mathematical models are developed to guide the design of training devices, the modeling of the effects to be expected for different configurations of a trainer will have to include the cue environment of the pilot. The finding that the particular conditions of motion cuing and visual delays used here have additive effects will make this modeling effort easier.

It was also encouraging to see clear effects of the visual delay variable. Again the measures of control input confirmed the trends seen in the error scores: that increasing the visual delay by about 62 milliseconds degraded control performance by about 10 percent. This is within the range expected from modeling efforts (Baron, Muralidharan, and Kleinman, 1980), but is slightly in excess of the effects seen in the control of fixed-wing systems by Queijo and Riley (1975). Undoubtedly the increased degradation reflects our use of a different flying task and a more unstable vehicle.

While the results of the motion cuing variable indicated the potential for the use of g-seats in helicopter simulations and the performance which could be obtained with a responsive motion platform, the results of the visual delay manipulation indicate that there are still benefits to be gained by trying to reduce delays in flight trainers. The 128.5 millisecond delay condition represented visual delays common in flight trainers today, and our data indicate the gain of steady state performance that might be expected as this delay is reduced by 62 milliseconds to a delay of about 66 milliseconds. A delay of 60 to 70 milliseconds in the visual scene is probably not beyond current technology for trainers equipped with computer generated visual displays, and the results we present here indicate the increase of control performance that might be expected with faster update rates both for the simulation and the display computers.

The results obtained by manipulating ship movement were a bit disappointing in that we had expected that the moving ship conditions would be more difficult to fly than they were. Undoubtedly this was because the amplitude of these motions was quite small. The development work for this experiment used a model of an aircraft carrier where the maximum excursion the g-seat pads could produce was characteristic of a sea state 3. Although the destroyer model was similarly mounted on the pads, it was shorter and the amplitude of the resulting motion was lower and representative of something between sea state 1 and sea state 2. This limitation was a product of using an amplitude-limited system to move the ship model and would not represent the case of a flight trainer equipped with a CGI visual system. Unfortunately, we could not address the problems which may arise when higher sea states are simulated.

Interestingly enough, effects due to the ship movement were detectable in the aircraft pitch angle and the rudder control inputs, and in the rest of the measures of control input when differences due to pilots were taken into account. For the most part, poorer control accompanied movement of the ship model, and a result most difficult to explain is the greater error of altitude seen with ship movement when the g-seat was used. This result was accompanied by less collective input when ship motion was off, and is representative of many of the ship motion effects. We did not anticipate them nor can we explain them satisfactorily.

Pilots were by far the largest source of variance in the study and most of the main effects of the experimental variables were qualified by their interactions with pilot differences. The traditional method of making subject differences and hopefully their interactions disappear is to create a variable along which subjects can differ. Subject effects have appeared in a host of human engineering studies, highlighting the need to examine (in this case) differences among pilots so that these subjects may be classified appropriately. The aim here would be to study the ways in which types of pilots react to changes of equipment variables so that a training device or system can be tailored to their needs or proclivities. With the current change to digitally controlled trainers and computer resident training information, this capability would not be difficult to implement, but to date, almost no information is available that would be of use. Pilots can certainly differ in as many ways as anyone else, but here we were thinking of types of behavior that represent stylized tendencies of aircraft control. Some pilots tend to use large, slow, and smooth movements of the controls, some use small quick movements, some respond faster than others, etc. Quite likely all of these characteristics are not independent random variables and a given individual could be assigned membership in a group by a cluster of these traits. Not only would the capability to do this make experiments more sensitive and useful, it would be a step toward individual training.

Throughout the experiment we questioned the pilots about their use of motion cues, their impressions of the task, what might make it easier, and the like. Four points seemed to come from that inquiry. While they represent subjective impressions that were gathered informally, they do come from experienced helicopter pilots and are worth mentioning. First, to a man, the pilots preferred the simulation when the motion platform was active. Not only was their impression one of greater realism, they felt that they produced their best performance with least effort when the base was active, as indeed they did. This is a common response in studies of platform motion and the high degree of consistency between the objective data and the pilots' impressions probably reflects the fact that the motion cues provided by the VMS represent the state of that art.

Second, again almost to a man, the pilots did not like the g-seat and felt that its use hurt their performance by providing false cues which they then had to ignore. This was not the case as the use of the g-seat did reduce their error scores by about five percent, but the fact that they formed this opinion probably reflects our scaling of the seat's response. During the preliminary work for this study, only one of the pilots could be used for the development of the seat's scaling, and this particular pilot had become quite skilled at

flying the VMS (his error scores were the lowest in the entire experiment). When the rest of the pilots started the experiment, a common finding was that the gain for the seat's response was set too high for the size of the g-forces they created, and the response of the seat was saturating, i.e. it inflated quickly to maximum and then deflated to its minimum. This happened often enough during the testing of the first pilot that we reduced the seat's gain by half. This placed most of the forces to be simulated within a dynamic range for which the seat gave graded responses, but the pilots still complained that the seat appeared "jerky" and lacked realism. Had more time been available for the development of the software to drive the seat, this shortcoming could have been overcome. During this study though it was never fully corrected. The fact that the use of the seat as a motion cuing device aided performance despite the pilots' unfavorable attitudes reinforces our belief that potential exists for g-seats to be used in fixed base trainers for helicopter operations.

Third, only about half of the pilots could tell when the ship model was moving, and when they could, they had no strong impression of whether or not their performance was better with the ship motion on or off. These impressions are consistent with the results of the analysis of the objective measures in that only small effects were produced by moving the ship model, and the causes of these effects were not always obvious. The pilots' lack of knowledge of the ship movement, like the small effects seen in the objective measures, most likely reflects the low amplitude of the model's movement--a condition which should be corrected in future work.

The last point concerns the field-of-view (FOV) needed to control a simulation of a helicopter landing on a small ship. The VMS allowed a 36^{o} vertical by 48^{o} horizontal forward FOV, and all of the pilots commented that a wider FOV would have made the flying task easier. Most often they stressed the need for peripheral visual cues that a side window would provide. Many of the pilots mentioned various techniques they used operationally for sampling peripheral visual cues--some of them looked out the side door (left open for safety reasons), others mentioned that they tended to fixate about 30^{o} to the right of straight-ahead, and still others just occasionally glanced out the side window. There are some data on the FOV needed for helicopter approach to landing. Gracy, Sommer, and Tibbs (1968) examined helicopter landing with a closed-circuit television system where the FOV could be reduced, and found little evidence that a restricted FOV hampered landing in an open field. But how to translate these results to landing on small ships is not clear. When unstable vehicles have to be controlled to narrow tolerances, the size of the visual field can be important. Clement, Heffley, and Jewell (1978) analyzed the FOV required for operational V/STOL aircraft to land on a destroyer class ship, and Stapleford, Clement, Heffley, Booth, and Fortenbaugh (1979), in a simulation study using the Flight Simulator for Advanced Aircraft at the Ames Research Center, commented that pilots felt that the narrow FOV of that device was too narrow for optimal approach performance.

While all of our pilots stressed the need for peripheral visual cues to aid the precise control needed as an aircraft got closer to the landing area, there were some differences of opinion concerning the priority which adding various windows to a trainer should have, and this centered about the

proposed use of the device. For a device to be used as an operational flight trainer, most pilots preferred a front window first, then the right side window, then the left front window, and finally the left side window. Should the device be used as a weapons system trainer where crew coordination is the task to be learned and the pilot's flight control is not all important, the priorities assigned to the left front and right side windows were reversed. In this case, the needs of the co-pilot should overrule the pilot's desire for peripheral cues.

We had no means to manipulate the FOV available in the VMS so the evidence in favor of a wide FOV represents expert opinion. Across several studies though, this has remained fairly constant: peripheral visual cues are used during the approach to a small ship landing area. If they are not provided, detecting small fore/aft translations is difficult and poor control usually results.

Occasionally throughout this discussion, we have stressed the advantages the use of models (in the mathematical sense) may have to support the development of training devices, and some more bits of information seen relevant here. Nataupsky, Waag, Weyer, McFadden and McDowell (1979) found no interaction of field-of-view and motion platform operation for the training of flying fixed wing aircraft. Again, the lack of interactions makes the development of such models easier. Some progress has been made as Heffley (1979) has successfully fitted the vertical trajectory data for helicopter approaches to hover by assuming certain perceptual transformations that pilots make on the size of objects. The point is that there is a need to predict how performance in a trainer can depend upon the cues the device can provide, and these results are a step in that direction.

This brings us to the last point to be stressed which is that we examined steady state performance under a variety of conditions that represented possible configurations of training devices, and we can order the performance to be expected from an average pilot in a trainer. Much of the need in designing training devices is for data that can relate a potential design of a trainer to the effectiveness of the training which the actual device will provide. That is, the training effectiveness of various cuing devices should be relatable to their costs, and to date, there are very few data which allow this. Requirements for cost effectiveness relations appear and develop far faster than data on the problem can accumulate, and studies such as the present one are performed on a specific problem with the faith that better performance in a trainer probably reflects a design that will produce better training. This need not be the case, and the results of studies of steady state performance should be carefully interpreted in the light of the training needs a particular device is intended to support. As transfer experiments are performed, the translation from steady performance to training effectiveness should become clearer.

SECTION V

CONCLUSIONS

Clearly the cues presented by the motion platform and g-seat of the VMS aided hover control and several conclusions are in order.

a. Because of its wide bandwidth and scheme for adaptive washout, the platform motion system of the VMS should not be considered standard. Its performance is beyond that to be expected for training equipment, and should the benefits shown by this study be desired, care should be taken in specifying the performance of a motion platform. The high performance of this system represents changes of software that exist and which would be possible to obtain for a trainer. G-seats need to be optimized for cuing the small rates and accelerations experienced during the low airspeed flight of approaches to landing of helicopters and V/STOL aircraft. G-seats represent new technology for trainers for these systems and research and development is needed for the seats to be useful. Work is needed on the drive logic, the scaling of the seat's responses for specific tasks, and the reduction of timing problems.

b. The algorithm to drive motion platform and g-seats is designed for high-speed coordinated flight yet there is no reason why they cannot be modified (by adjusting the gain or washout rules) for the simulation of hover or low airspeed flight. Typically the rotation vehicles experience under these regimes are small and could be simulated on a one-for-one basis with current platform technology. G-seats, especially those with rotatable seat pans, have potential for simulating low-g environments as demonstrated by these data. The logic to operate both systems could be made adaptive as a function of airspeed or ground speed so that the platform or seat would provide useful cuing over the entire flight envelope of the vehicle simulated.

c. Visual delays shorter than 128 milliseconds clearly can result in better hover control, and if a CIG visual system will be used in trainers for helicopter aircrews, attention should be paid to its update rate (as well as that of the aerodynamic simulation). This could mean that a large system should operate at 60 Hz or that each window of a trainer display system should have its own processor, or whatever. The point is that the shorter the total delay, the better.

d. The lack of major effects due to ship motion may not be indicative of what to expect when high sea states are simulated, especially if a trainer is used to train night landing or operation with the stability augmenting equipment disabled. Such operations are dangerous and these are good candidates for tasks to be trained in a simulator. A helicopter is like an unstable second-order system without its stability augmentation, for instance, and under such conditions we would expect motion cuing to be more useful possibly than we have shown here or more difficulty may be created by motion of the ship than indicated here.

e. We expect that these results could be comfortably extended to simulations of systems that act like helicopters--for instance, V/STOL aircraft during conversion or thrust-supported flight. Because of the similarity of

its flying task, its instability, and the workload the pilot experiences in controlling the aircraft, we would expect that the relations shown for this simulation of the AH-1 helicopter would be similar to what might be found for simulations of other marginally stable vehicles. Thus the data of this report may be useful for the development of flight trainers for other aircraft.

f. Clearly, subject differences should be expected in human engineering work and research studies should be designed to isolate them. More useful for the future would be work to describe these differences in ways that would allow pilots to be easily classified. The results of research could then be more generalizable by being more true for specific sets of subjects.

g. The relation between performance and transfer has never been determined clearly enough to be used in the design process of training devices, and it would be advisable to use the equipment for which we have data for a transfer experiment. Then at least for one flying task, steady state control, transfer effectiveness, and costs could all be related in a manner useful for planning.

h. A last recommendation has to do with models to guide engineering development. Effort is underway to incorporate the data of this study into a piloting control model to predict the effects produced by simulation equipment like motion cuing devices. This would extend the analysis of Baron, Lancraft and Zacharias (1980). Incorporating into this model other sorts of simulation devices and flying tasks would be a useful exercise and could produce a tool useful for evaluating various design options for flight trainers.

SECTION VI

RECOMMENDATIONS

From these data, a motion platform seems the best technology for cuing aircraft motion for simulations of marginally stable vehicles. The logic that controls the platform should be optimized for the simulation of uncoordinated flight when they are used for hover or similar flying tasks.

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APPENDIX A

EQUATIONS AND PARAMETERS

Here are presented the drive equations for the g-seat and ship motion, including the amplitudes and frequencies of the components for the sea state 3 simulation. Also presented are the parameters chosen to drive the adaptive washout of the motion platform of the VMS.

TABLE A-1. WASHOUT PARAMETERS FOR THE MOTION PLATFORM

Except for rare instances, the symbols here are consistent with those used by Schmidt and Conrad (1970). Exceptions are described in Martin (1977).

Symbol	Parameter	Value	Units
R_x	Components of vector from aircraft center of gravity to motion-base centroid	1.2192	m
R_y		0.6858	m
R_z		1.7399	m
x_1	Longitudinal breakpoint	3.6576	m/sec^2
$S_{x,o}$	Longitudinal scale factor	1.0	
y_1	Lateral breakpoint	2.4384	m/sec^2
$S_{y,o}$	Lateral scale factor	1.0	
Z_1	Vertical breakpoint	2.7432	m/sec^2
$S_{z,o}$	Vertical scale factor	1.0	
p_1	Roll breakpoint	0.18	rad/sec
$S_{p,o}$	Roll scale factor	1.0	
q_1	Pitch breakpoint	0.5	rad/sec
$S_{q,o}$	Pitch scale factor	1.0	
r_1	Yaw breakpoint	0.15	rad/sec
$S_{r,o}$	Yaw scale factor	1.0	
W_x	Pitch rate weight	61.69	$m^2/rad^2\text{-}sec^2$
b_x	Longitudinal position penalty	0.1	sec^{-4}

TABLE A-1. WASHOUT PARAMETERS FOR THE MOTION PLATFORM (cont'd)

Symbol	Parameter	Value	Units
c_x	Longitudinal velocity penalty	2.0	sec^{-2}
d_x	Longitudinal damping	1.2727	rad/sec
e_x	Longitudinal frequency	0.81	rad/sec^2
γ_x	Longitudinal coordination gain	0.03281	rad-sec/m
$K\lambda,x$	Longitudinal gains	0.517	sec^3/m^2
$K\delta,x$		0.7535	sec^3/m^2
$K_{i,\lambda,x}$	Longitudinal gains on initial parameters	0.05	sec^{-1}
$K_{i,\delta,x}$		0.5	sec^{-1}
$\lambda_{x,MIN}$	Limits on longitudinal variables	-0.1	
$\lambda_{x,MAX}$		0.8	
$\delta_{x,MIN}$		0.0	
$\delta_{x,MAX}$		0.3	
$\dot{\lambda}_{x,MIN}$		-0.06	
$\dot{\delta}_{x,MIN}$		-1000.	
$\lambda_x(o)$	Initial conditions	0.8	
$\delta_x(o)$		0.3	
W_y	Roll rate weight	0.00929	m^2/rad^2-sec^2
b_y	Lateral position penalty	0.1	sec^{-4}
c_y	Lateral velocity penalty	2.0	sec^{-2}
d_y	Lateral damping	1.2727	rad/sec
e_y	Lateral frequency	0.81	rad/sec^2
γ_y	Lateral coordination gain	0.03281	rad-sec/m
$K\lambda,y$	Lateral gains	0.517	sec^3/m^2
$K\delta,y$		0.269098	sec^3/m^2

TABLE A-1. WASHOUT PARAMETERS FOR THE MOTION PLATFORM (cont'd)

Symbol	Parameter	Value	Units
$K_{i,\lambda,y}$	Lateral gains on initial parameters	0.05	sec^{-1}
$K_{i,\delta,y}$		1.5	sec^{-1}
$\lambda_{y,MIN}$	Limits on lateral variables	-0.1	
$\lambda_{y,MAX}$		0.2	
$\delta_{y,MIN}$		0.0	
$\delta_{y,MAX}$		0.3	
$\dot{\lambda}_{y,MIN}$		-0.06	
$\dot{\delta}_{y,MIN}$		-0.2	
$\lambda_y(o)$	Initial conditions	0.2	
$\delta_y(o)$		0.3	
b_z	Vertical position penalty	0.5*	sec^{-4}
c_z	Vertical velocity penalty	0.1*	sec^{-2}
d_z	Vertical damping	1.2727*	rad/sec
e_z	Vertical frequency	0.81*	rad/sec^2
$K_{\eta,z}$	Vertical gain	10.7639*	sec^3/m^2
$K_{i,\eta,z}$	Vertical gain on initial parameter	0.05*	sec^{-1}
$\eta_{z,MIN}$	Limits on vertical variables	-0.1*	
$\eta_{z,MAX}$		1.0*	
$\dot{\eta}_{z,MIN}$		-0.06*	
$\eta_z(o)$	Initial condition	1.0*	
b_ψ	Yaw position penalty	1.0	sec^{-4}
e_ψ	Yaw time constant	0.3	rad/sec^2

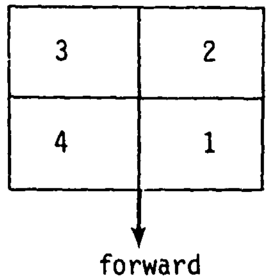
*The calculation of $F_{i,z}$ (the inertial transformation of A_z) was replaced by a circuit to detect movement of the collective. The resultant position output was mixed with the rotor vibration signal to provide the vertical drive signal for the motion platform.

TABLE A-1. WASHOUT PARAMETERS FOR THE MOTION PLATFORM (cont'd)

Symbol	Parameter	Value	Units
$K_{\eta,\psi}$	Yaw gain	100.	sec/rad^2
$K_{i,\eta,\psi}$	Yaw gain on initial parameter	0.1	sec^{-1}
$\eta_{\psi,MIN}$	Limits on yaw variables	0.0	
$\eta_{\psi,MAX}$		1.0	
$\dot{\eta}_{\psi,MIN}$		-0.4	
$\eta_{\psi}(o)$	Initial condition	1.0	
$C_{x,A}$	Lead compensation parameters	0.0069	sec^2
$C_{y,A}$		0.0069	sec^2
$C_{z,A}$		0.0069	sec^2
$C_{x,v}$		0.15	sec
$C_{y,v}$		0.15	sec
$C_{z,v}$		0.133	sec
C_{ψ}		0.12	sec
C_{θ}		0.12	sec
C_{ϕ}		0.12	sec
g	Gravitational constant	9.806178	m/sec^2
h	Program step size	0.03125	sec

TABLE A-2. G-SEAT DRIVE EQUATIONS

Numbering of the g-seat cells



$$\text{CELL } 1 = K_p\,\dot{\theta}_+ + K_r\,\dot{\phi}_- + K_1 A_{x+}$$

$$\text{CELL } 2 = K_p\,\dot{\theta}_- + K_r\,\dot{\phi}_- + K_1 A_{x-}$$

$$\text{CELL } 3 = K_p\,\dot{\theta}_- + K_r\,\dot{\phi}_+ + K_1 A_{x-}$$

$$\text{CELL } 4 = K_p\,\dot{\theta}_+ + K_r\,\dot{\phi}_+ + K_1 A_{x+}$$

where $\dot{\theta}$ = Aircraft Pitch Rate

$\dot{\phi}$ = Aircraft Roll Rate

A_x = Aircraft Vertical Acceleration

and
$$\dot{\theta}_+ = \begin{cases} \dot{\theta}, & \dot{\theta} \geq 0 \\ 0, & \dot{\theta} < 0 \end{cases} \qquad \dot{\theta}_- = \begin{cases} 0, & \dot{\theta} > 0 \\ \dot{\theta}, & \dot{\theta} \leq 0 \end{cases}$$

and
$$\dot{\phi}_+ = \begin{cases} \dot{\phi}, & \dot{\phi} \geq 0 \\ 0, & \dot{\phi} < 0 \end{cases} \qquad \dot{\phi}_- = \begin{cases} 0, & \dot{\phi} > 0 \\ \dot{\phi}, & \dot{\phi} \leq 0 \end{cases}$$

and
$$K_p = 1.0\ \frac{\text{sec}}{\text{rad}},\ K_r = 1.7\ \frac{\text{sec}}{\text{rad}},\ K_1 = 6.44 \text{ per g}$$

The + and - subscripts indicate when a variable contributes to a cell's response. For Cell 1, for instance, $\dot{\theta}$ only affects the cell's operation when $\dot{\theta}$ is greater than zero. For Cell 2, $\dot{\theta}$ only contributes when it is less than zero.

TABLE A-3. SHIP MOVEMENT DRIVE EQUATIONS

The g-seat's four bladders, numbered in Table A-2, are controlled independently. The bow of the ship was connected to bladder #2 and the stern to bladder #4. Bladders 1 and 3 provided roll and heave motion by means of a cross-brace connected to the center of the ship. The bladder drive equations were:

drive 1 = $K_Z\ Z_S + K_\phi \phi_S$ + ref

drive 2 = $K_Z\ Z_S + K_\theta \theta_S$ + ref

drive 3 = $K_Z\ Z_S + K_\phi \phi_S$ + ref

drive 4 = $K_Z\ Z_S + K_\theta \theta_S$ + ref

where K_Z is the gain on the vertical motion, z_S $K_Z = 1.0$

K_θ is the gain on the pitch motion, θ_S $K_\theta = 2.0$

K_ϕ is the gain on the roll motion, ϕ_S $K_\phi = 0.$

The pitch, roll and heave motion equations were adapted from reference 14. As adapted, the equations were:

$$m_i = \sum_{j=1}^{4} A_{ij} \cos (\omega_j t - \phi_{ij} + \varepsilon_j)$$

where i = axis identification (pitch, roll, or heave)

j = component number

m_i = ship motion about mean position in i<u>th</u> axis (Zs, ϕs, θs)

A_{ij} = amplitude associated with j component of i<u>th</u> axis

ω_j = encounter frequencies associated with j<u>th</u> component

t = time

ϕ_{ij} = phase angle for j<u>th</u> component in i<u>th</u> axis

ε_j = uniformly distributed random phase, ±180°, selected at the beginning of each run for the four components.

TABLE A-3. SHIP MOVEMENT DRIVE EQUATIONS (cont'd)

The following amplitudes, frequencies, and phases were utilized for sea state 3 (condition 11 of Fortenbaugh, 1978).

j		1	2	3	4
ωj, rad/sec		.70	.89	1.10	1.32
Amplitude,	pitch, deg	.175	.339	.293	.112
A_{ij}	roll, deg	.537	.572	.342	.136
	heave, meters	.179	.275	.240	.051
Phase,	pitch, deg	-62.95	-44.14	-4.82	27.56
ϕij	roll, deg	-82.25	-63.80	-62.17	-72.97
	heave, deg	-1.39	2.13	40.13	81.84

Maximum resultant motion at the landing pad was about 5 feet, of which 2 feet was fixed vertical motion and 3 feet was pitch induced (estimates).

APPENDIX B

UNIVARIATE ANALYSES OF VARIANCE TABLES

These tables document the univariate analyses of variance performed on each of our ten measures. For F-ratios significant at the $p<.05$ level, the exact probability of the ratio (rounded to four places) is provided. In all of these analyses, only pilots were considered a random variable, and in the tables, Reps = replications, P = pilots, S = ship motion, M = motion conditions, and D = visual delay.

TABLE B-1. ANALYSIS OF THE RMS VALUE OF SHIP-LATERAL (y) POSITION OF THE HELICOPTER

Source	SS	DF	MS	F	Prob
Reps	233.80	4	58.45	4.14	.0029
P	3846.59	11	349.69	24.79	.0000
S	14.74	1	14.74	1.04	
PxS	82.94	11	7.54	.53	
D	186.53	1	186.53	13.22	.0006
PxD	524.48	11	47.68	3.38	.0003
SxD	135.37	1	135.37	9.60	.0025
PxSxD	164.01	11	14.91	1.06	
M	545.60	2	272.80	19.34	.0000
PxM	1217.48	22	55.34	3.92	.0000
SxM	13.14	2	6.57	.47	
PxSxM	496.76	2	22.58	1.60	.0409
DxM	27.34	2	13.67	.99	
PxDxM	463.54	22	21.07	1.49	
SxDxM	91.04	2	45.52	3.23	.0390
PxSxDxM	280.06	22	12.73	.90	
Error	8070.92	572	14.11		
Total	16394.34	719			

TABLE B-2. ANALYSIS OF THE RMS VALUE OF THE BOW-STERN (x) POSITION OF THE HELICOPTER

Source	SS	DF	MS	F	Prob
Reps	104.24	4	26.06	1.90	
P	3695.78	11	335.98	24.51	.0000
S	12.81	1	12.81	.93	
PxS	137.94	11	12.54	.91	
D	182.25	1	182.25	13.30	.0006
PxD	519.53	11	47.23	3.44	.0003
SxD	103.21	1	103.21	7.53	.0064
PxSxD	303.82	11	27.62	2.01	.0252
M	921.52	2	460.76	33.61	.0000
PxM	1085.92	22	49.36	3.60	.0000
SxM	2.42	2	1.21	.09	
PxSxM	667.70	22	30.35	2.21	.0015
DxM	35.24	2	17.62	1.29	
PxDxM	220.22	22	10.01	.73	
SxDxM	27.52	2	13.76	1.00	
PxSxDxM	468.16	22	21.28	1.55	
Error	7842.12	572	13.71		
Total	16323.40	719			

TABLE B-3. ANALYSIS OF THE RMS VALUE OF THE ALTITUDE OF THE HELICOPTER

Source	SS	DF	MS	F	Prob
Reps	7.4	4	1.85	.93	
P	531.52	11	48.32	24.26	.0000
S	7.03	1	7.03	3.53	
PxS	17.60	11	1.60	.81	
D	37.25	1	37.25	18.71	.0001
PxD	114.18	11	10.38	5.21	.0000
SxD	.57	1	.57	.29	
PxSxD	19.14	11	1.74	.88	
M	51.62	2	25.81	12.96	.0000
PxM	73.48	22	3.34	1.68	.0270
SxM	15.98	2	7.99	4.01	.0182
PxSxM	45.54	22	2.07	1.04	
DxM	10.04	2	5.02	2.52	
PxDxM	33.66	22	1.53	.77	
SxDxM	7.36	2	3.68	1.85	
PxSxDxM	77.22	22	3.51	1.76	.0177
Error	1138.28	572	1.99		
Total	2187.87	719			

TABLE B-4. ANALYSIS OF THE RMS VECTOR POSITION OF THE HELICOPTER

Source	SS	DF	MS	F	Prob
Reps	331.16	4	82.79	3.50	.0080
P	7517.73	11	683.43	28.92	.0000
S	31.76	1	31.76	1.34	
PxS	187.11	11	17.01	.72	
D	425.83	1	425.83	18.02	.0001
PxD	1104.07	11	100.37	4.25	.0000
SxD	325.58	1	235.58	9.97	.0021
PxSxD	391.82	11	35.62	1.51	
M	1500.08	2	750.04	31.74	.0000
PxM	2216.94	22	100.77	4.26	.0000
SxM	18.02	2	9.01	.38	
PxSxM	1003.20	22	45.60	1.93	.0070
DxM	44.64	2	22.32	.94	
PxDxM	466.02	22	21.21	.90	
SxDxM	118.70	2	59.35	2.51	
PxSxDxM	642.18	22	29.19	1.24	
Error	13516.36	572	23.63		
Total	29751.80	719			

TABLE B-5. ANALYSIS OF THE RMS ROLL ANGLE OF THE HELICOPTER

Source	SS	DF	MS	F	Prob
Reps	.00108	4	.00027	1.32	
P	.05302	11	.00482	23.74	.0000
S	.00019	1	.00019	.94	
PxS	.00528	11	.00048	2.37	.0074
D	.00932	1	.00932	45.92	.0000
PxD	.00517	11	.00047	2.31	.0091
SxD	.00001	1	.00001	.06	
PxSxD	.00495	11	.00045	2.23	.0120
M	.00498	2	.00249	12.30	.0001
PxM	.0088	22	.00040	1.95	.0063
SxM	.00046	2	.00023	1.12	
PxSxM	.01386	22	.00063	3.09	.0000
DxM	.00096	2	.00048	2.39	
PxDxM	.00594	22	.00027	1.32	
SxDxM	.00092	2	.00046	2.24	
PxSxDxM	.0077	22	.00035	1.73	.0208
Error	.1144	572	.00020		
Total	0.237	719			

TABLE B-6. ANALYSIS OF THE RMS PITCH ANGLE OF THE HELICOPTER

Source	SS	DF	MS	F	Prob
Reps	.000216	4	.000054	.69	
P	.028996	11	.002636	33.76	.0000
S	.00050	1	.00050	6.40	.0113
PxS	.000946	11	.000086	1.11	
D	.00072	1	.00072	9.22	.0029
PxD	.002992	11	.000272	3.48	.0002
SxD	.000245	1	.000245	3.14	
PxSxD	.001188	11	.000108	1.38	
M	.000042	2	.000021	.27	
PxM	.005038	22	.000229	2.93	.0001
SxM	.000276	2	.000138	1.77	
PxSxM	.004268	22	.000194	2.49	.0004
DxM	.00018	2	.000090	1.16	
PxDxM	.001628	22	.000074	.95	
SxDxM	.000176	2	.000088	1.13	
PxSxDxM	.0033	22	.00015	1.92	.0074
Error	.044616	572	.000078		
Total	0.0959	719			

TABLE B-7. ANALYSIS OF THE RMS VALUE OF THE FORE/AFT POSITIONS OF THE CYCLIC CONTROL

Source	SS	DF	MS	F	Prob
Reps	.0336	4	.0084	.88	
P	9.361	11	.851	88.8	.0000
S	.0276	1	.0276	2.88	
PxS	.3256	11	.0296	3.09	.0007
D	.196	1	.196	20.46	.0001
PxD	.7359	11	.0669	6.98	.0000
SxD	.0207	1	.0207	2.16	
PxSxD	.4961	11	.0451	4.71	.0000
M	.1432	2	.0716	7.47	.0010
PxM	.8470	22	.0385	4.02	.0000
SxM	.0418	2	.0209	2.18	
PxSxM	.4268	22	.0194	2.03	.0041
DxM	.0658	2	.0329	3.43	.0320
PxDxM	.5434	22	.0247	2.58	.0002
SxDxM	.0566	2	.0283	2.95	
PxSxDxM	.2606	22	.0573	5.98	.0000
Error	.4912	572	.0096		
Total	20.06	719			

TABLE B-8. ANALYSIS OF THE RMS VALUE OF THE LATERAL POSITIONS OF THE CYCLIC CONTROL

Source	SS	DF	MS	F	Prob
Reps	.0788	4	.0197	3.58	.0070
P	7.3645	11	.6695	121.42	.0000
S	.0147	1	.0147	2.66	
PxS	.4884	11	.0444	8.05	.0000
D	.1073	1	.1073	19.46	.0001
PxD	.1991	11	.0181	3.28	.0004
SxD	.0061	1	.0061	1.10	
PxSxD	.3135	11	.0285	5.18	.0000
M	.5556	2	.2778	50.39	.0000
PxM	.7458	22	.0339	6.15	.0000
SxM	.0294	2	.0147	2.67	
PxSxM	.3982	22	.0181	3.29	.0000
DxM	.0278	2	.0139	2.53	
PxDxM	.2662	22	.0121	2.19	.0017
SxDxM	.0864	2	.0432	7.84	.0007
PxSxDxM	.5082	22	.0231	.19	.0000
Error	3.146	572	.0055		
Total	14.36	719			

TABLE B-9. ANALYSIS OF THE RMS VALUE OF THE POSITIONS OF THE RUDDER PEDALS

Source	SS	DF	MS	F	Prob
Reps	.001	4	.00025	1.12	
P	.05247	11	.00477	21.61	.0000
S	.00128	1	.00128	5.80	.0155
PxS	.00891	11	.00081	3.68	.0001
D	.00501	1	.00501	22.72	.0000
PxD	.01507	11	.00137	6.21	.0000
SxD	.00047	1	.00047	2.12	
PxSxD	.0099	11	.00090	4.06	.0001
M	.0005	2	.00025	1.12	
PxM	.01936	22	.00088	3.99	.0000
SxM	.00058	2	.00029	1.29	
PxSxM	.00748	22	.00034	1.52	
DxM	.00004	2	.00002	.08	
PxDxM	.01628	22	.00074	3.37	.0000
SxDxM	.00178	2	.00089	4.06	.0174
PxSxDxM	.01166	22	.00053	2.41	.0005
Error	.12584	572	.00022		
Total	0.277	719			

TABLE B-10. ANALYSIS OF THE STANDARD DEVIATION OF THE POSITION OF THE COLLECTIVE CONTROL

Source	SS	DF	MS	F	Prob
Reps	.1544	4	.0386	.98	
P	14.52	11	1.320	33.63	.0000
S	.1240	1	.1240	3.16	
PxS	1.8656	11	.1696	4.32	.0000
D	.6950	1	.6950	17.71	.0001
PxD	3.7499	11	.3409	8.68	.0000
SxD	.2030	1	.2030	5.17	.0220
PxSxD	1.9239	11	.1749	4.46	.0000
M	.1304	2	.0652	1.66	
PxM	2.3122	22	.1051	2.68	.0001
SxM	.3668	2	.1834	4.67	.0099
PxSxM	1.5598	22	.0709	1.81	.0135
DxM	.1286	2	.0643	1.64	
PxDxM	1.727	22	.0785	2.0	.0048
SxDxM	.01	2	.0050	.13	
PxSxDxM	2.1582	22	.0981	2.5	.0004
Error	22.4796	572	.0393		
Total	54.1084	719			

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